Survey on clad component design procedures for nuclear and non-nuclear applications

Experimental Operations and Facilities Division

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ABSTRACT

Corrosion resistant weld overlay and integral claddings are used to provide corrosion resistance to components made of structural materials that are susceptible to corrosion. Generally, cladding is used in industry to offset the cost of expensive corrosion resistance alloys. In the application to nuclear, cladding provides a mechanism to allow use of limited code approved base materials in corrosive environments. Applicable design rules will need to be developed to support the design and construction of these cladded components for MSR applications. This document provides a survey of the state-of-the-art in design practice of cladded components for both the nuclear and non-nuclear industry. Design practice and service experience in the nuclear and non-nuclear is investigated. A gap analysis on applying these design practice to nuclear applications is included.

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1 Abbreviations

BPVC	ASME Boiler and Pressure Vessel Code
CRA	Corrosion Resistant Alloy
ESW	Electroslag Arc Welding
FCAW	Flux-Cored Arc Welding
FEA	Finite Element Analysis
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
LWR	Light Water Reactor
MSR	Molten Salt Reactor
PWHT	Post Weld Heat Treatment
RPV	Reactor Pressure Vessel
SAW	Submerged Arc Welding
S_a	Maximum allowable stress
S_b	Maximum allowable stress of the base metal
S_c	Maximum allowable stress of the cladding
SCL	Stress Classification Lines
SMAW	Submerged Metal Arc Welding

2 Terms and Definitions

Integral cladding - Refers to metallic lining material that forms a metallurgical bond with the base metal during manufacture. This is typically accomplished using hot roll bonding or explosion bonding techniques. This is different than weld overlay cladding which is defined below.

Weld Overlay Cladding - Refers to the application of a metallic lining material using a weld deposition process that forms a metallic bond with the base metal. Thickness is generally greater than 3 mm.

Loose lining - Refers to the application of a metallic lining material that is not integrally bonded with the base metal. These lining are typically attached to the base metal by fillet welds and possibly some plug welds. Linings are not integrally attached and are either intermittently attached or not attached at all.

Back cladding - Term used for weld overlaying the exposed base metal at weld joints, such as circumferential and longitudinal seams and nozzles, of integrally clad equipment. The weld overlay provides the corrosion barrier over the base metal joints. Back cladding is typically not applicable for reactive metals, such as titanium, zirconium, and tantalum. Back cladding generally follows the same requirements as weld overlaying.

Hot Cracking - Shrinkage cracks that occur during solidification.

3 Introduction

Corrosion resistant weld overlay and integral claddings are used to provide corrosion resistance to components made of structural materials that are susceptible to corrosion. Generally, cladding is used in industry to offset the cost of expensive corrosion resistance alloys. In the application to nuclear, cladding provides a mechanism to allow use of limited code approved base materials in corrosive environments.

Such cladding is used to provide corrosion resistance for pressure vessels in nuclear (low temperature) and non-nuclear (high temperature) applications. Weld-overlay cladding applications include the internal surfaces of reactor pressure vessels (RPV) and tubesheets of shell and tube heat exchangers. Applicable design rules will need to be developed to support the design and construction of these clad components for MSR applications. To address these needs, R&D is being conducted to develop new design and construction rules and analysis methods for clad structure to ascertain the integrity, and hence the corrosion protective function, of the cladding for the anticipated service lifetime and cyclic service conditions in MSR.

Section 8 of the ASME BPVC (ASME, 2017), (ASME, 2017), ANSI B31.1 Code for Power Piping (ASME, 2016), and ANSI B31.3 Code for Pressure Piping (ASME, 2016) provide the main references for industry. The ASTM provides a standard for integrally clad plate. ASME BP&V code section IX provides weld fabrication procedure and inspection requirements.

Cladding is covered both in Division 1 and Division 2 of Section VIII of the BPVC (VIII-1 and VIII-2 respectively). VIII-1 specifies a simplified set of design rules and formulas relies on conservatism and a higher design margin to account for these simplifications. The formulas are created with standard pressure vessel component geometries in mind. VIII-2 is organized by Parts and provides two approaches to design: Design by Rule and Design by Analysis. In both cases, the design margins are lower due to the more rigorous analysis. VIII-2 Part 4 provides formulas for Design by Rule much like VIII-1 however here the formulas and rules are much more rigorous. Similar to VIII-1, the formulas are developed with standard pressure vessel geometries in mind. VIII-2 Part 5 is geometry independent and based purely on stress analysis. In particular, it readily admits the use of computational techniques such as FEA.

In summary, there are three paths through Section 8: VIII-1, VIII-2 Part 4, and VIII-2 Part 5. In all three of these approaches, cladding is allowed both as integral clad plate or weld overlay cladding. Further, in each approach, there are provisions for inclusion of the cladding thickness in the strength calculation of the component if desired. The details of the three approaches are discussed in Sections 4 and 5.

The ANSI B31 codes for piping (B31.1 and B31.3) are comparable in approach to the BPVC and refer back to the BPVC for material specifications and weld instructions. These rules are covered in Section 0.

A gap analysis on applying these design practice to nuclear applications is included.

4 Section VIII Division 1

A flowchart is provided Figure 12-1 to provide an easy overview and comparison of the different paths through VIII-1. There are four paths depending upon the choices of cladding method (weld-overlay, integral cladding, or liner) and then if it is desired to include the cladding thickness in the strength calculation of the component.

The requirements for clad pressure vessels or vessel parts that are constructed of base material with corrosion resistant integral or weld metal overlay cladding are covered in Part UCL. This also includes vessels and vessel parts that are fully or partially lined inside or outside with corrosion resistant plate, sheet, or strip, attached by welding to the base plates before or after forming or to the shell, heads, and other parts during or after assembly into the completed vessel. These rules do not indicate the selection of an alloy suitable for the intended service or the amount of the corrosion allowance to be provided. Users must determine suitability for application.

Referring to Figure 12-1, we see that materials for the base material are constrained to carbon and low alloy steels, heat treated ferretic steels, and forgings of carbon, low-alloy, and high alloy steels independent upon cladding method or use of a liner.

After noting the constraint on base material, there is a branch in Figure 12-1 where the analysis path varies depending upon whether the cladding thickness will be used. For the case of a liner, it is not an option. Similarly, one can elect to neglect the cladding thickness. When the base material only is used for determining the cladding thickness, there is no constraint on the cladding material.

The right two branches of the flow chart describe the path where one takes credit for the cladding thickness in calculating the design thickness. This is possible when the integral clad plate conforms to one of the three specifications, SA-263, SA264, SA-265¹ or use weld metal overlay cladding meeting specific requirements stated in Division 1. The integral clad specifications are base plate made of a carbon or low-alloy steel specification used for pressure vessels². The cladding families include stainless chromium steel, stainless chromium-nickel, and nickel or nickel-based alloys. Integral clad plate must have a minimum shear strength of 140 MPa test requirement following the shear test illustrated in Figure 12-4. No shear test requirement exists for weld overlay.

In addition to the above requirements for the integral clad plate, joints between clad plates must be completely covered by corrosion resisting weld material over the base plate to restore the cladding. In the event that the cladding material made up of multiple welded plates, the cladding welds must be examined over the full length either use radiography (as prescribed in UW-51³) or ultrasound (UW-53) prior to bonding the cladding to the base material. The welding must be performed by an authorized manufacturer and a partial data report supplied if not done by the vessel manufacturer.

When including the cladding thickness in the design calculation, consideration is given to the difference in strength of the cladding and base plate material. The thickness used for the design calculation, t , is defined as:

$$t = t_b + \frac{S_C}{S_B} t_c \quad (4.1)$$

Where:

- t: Design thickness
- t_b : Nominal base metal thickness
- t_c : Nominal cladding thickness less any allowance for corrosion

¹ SA-263, -264, or -265 correspond to ASTM-A263, -A264, and -A265 for practical purposes.

² Table UCS-23 lists the Carbon and Low Alloy Steel specifications for Sect. VIII Div.1

³ Refers to sections in VIII-1.

S_c : Allowable stress of the clad material at design temperature

S_b : Allowable stress of the base material at design temperature

Note that S_c/S_b is taken as unity when $S_c > S_b$ and the allowable stress of the weaker material must be no less than 70% that of the stronger material. From this formula, we see that there is a reduction factor applied when the cladding material is weaker than the base material, but no credit is allowed for stronger cladding.

Allowable stress for the base plate is determined from Section II, Part D, Table 1A⁴. When weld overlay cladding is used, the maximum allowable stress of the cladding, S_c , is taken as taken from the material stress tables by selecting the wrought material whose chemistry matches the cladding the most closely. For integral cladding, the allowable stress is taken from the cladding material specification.

As an example of the application of this formula, consider the basic calculation for thickness of a shell under internal pressure loading dominated by circumferential stress where the thickness is given by the following formula⁵:

$$t = \frac{PR}{SE - 0.6P} \quad (4.2)$$

Where:

t : Design thickness

P : Pressure

R_c : Internal Radius

S : Maximum allowable stress of the base material

E : weld joint efficiency.

Using equation (4-1), the equivalent thickness, t , required in equation (4-2) can be determined as a combination of the base metal thickness, t_b , and the cladding thickness, t_c .

When the cladding thickness is considered in the thickness calculation, the maximum design temperature is based upon the minimum of the base and clad materials. If the cladding is not included in the determination of the thickness, then the maximum allowable temperature of the base

⁴ Base material specified in tables UCS-23, UHA-23, or UHT-23

⁵ UG-27 formula 1.

material determines the service temperature. Section VIII Div. 1 recommends against the use of chromium-alloy stainless steel with greater than 14% chromium content to be used beyond 425°C.

5 Section VIII Division 2

As mentioned above, Division 2 of the code provide two approaches for designing components. Part 4, Design By Rule, is a rule/formula based method that covers commonly used pressure vessel shapes and geometries. Part 5, Design By Analysis based upon stress analysis and can be applied independent of geometry. Both Part 4 and Part 5 require more rigorous analysis than Section VIII Div. 1. This additional analysis of Div. 2 results in a more optimal design in terms of material use. The additional benefit of Part 5 is that it allows all geometry. Division 2 defines two classes of vessels, Class 1 and Class 2. Class 2 vessels have lower design margin versus ultimate. Part 5 is generally reserved for Class 2 vessels except for cases where Part 4 rules do not apply such as for a given geometry. There are limitations to using the rules of Part 5 when using allowable stress determined from time-dependent material properties.

Similar to the previous section, Figure 12-2 provides a flow chart describing the analysis paths through VIII-2. The base materials are limited to carbon and low-alloy materials (Table 3-A.1 in VIII-2). Referring to the flowchart, there five paths through VIII-2. As in VIII-1, the first option is to ignore the cladding thickness. The remaining four paths include the cladding in the design thickness with the path depending upon the choice of analysis method (Part 4: Design by Rule or Part 5: Design by Analysis) and choice of cladding method (weld-overlay or integral cladding).

5.1 Part 4 - Thickness in design calculation including cladding

Using the Design by Rule methodology of VIII-2 Part 4, it is possible to take credit for the cladding thickness in calculating the design thickness. This is possible when the integral clad plate conforms to one of the listed specifications (SA-263, SA-264, SA-265)⁶ or use weld metal overlay cladding meeting specific requirements stated in Division 2. This implies weld qualification specified of VIII-2 (in 6.2.2.4⁷). Similar to that of VIII-1, the thickness used for the design calculation, t , is defined as:

$$t = t_b + \frac{S_c}{S_B} t_c \quad (5.1)$$

Where:

⁶ SA-263, -264, or -265 correspond to ASTM-A263, -A264, and -A265 for practical purposes.

⁷ Refers to sections in VIII-2.

- t: Design thickness
- t_b: Nominal base metal thickness
- t_c: Nominal cladding thickness less any allowance for corrosion
- S_c: Allowable stress of the clad material
- S_b: Allowable stress of the base material

Note that S_c/S_b is taken as unity when S_c > S_b and the allowable stress of the weaker material must be no less than 70% that of the stronger material. From this formula, we see that there is a reduction factor applied when the cladding material is weaker than the base material, but no credit is allowed for stronger cladding.

Allowable stress for the base plate is determined from Section II, Part D, Tables 2A, 2B for Class 1 components and Tables 5A and 5B for Class 2 components⁸. The allowable stress, S_c, for the cladding on integral cladding is similarly determined from the same tables based upon the specification of the cladding. When weld overlay cladding is used, the maximum allowable stress of the cladding, S_c, is taken as taken from the same stress tables by selecting the wrought material whose chemistry matches the cladding the most closely.

As an example of the application of this formula, consider the basic calculation for thickness of a shell under internal pressure loading dominated by circumferential stress where the thickness is given by the following formula⁹:

$$t = \frac{D}{2} \left(\exp \left[\frac{P}{SE} \right] - 1 \right) \quad (5.2)$$

Where:

- t : Design thickness
- P : Pressure
- R_c : Internal Radius
- S : Maximum allowable stress of the base material
- E : weld joint efficiency.

⁸ Base material specified in tables 3-A.1 through 3-A.7.

⁹ Equation 4.3.1 from Section VIII, Div. 2, Part 4.

Using equation (5-1), the equivalent thickness, t , required in equation (5-2) can be determined as a combination of the base metal thickness, t_b , and the cladding thickness, t_c .

Joints between clad plates must be completely covered by corrosion resisting weld material over the base plate to restore the cladding. In the event that the cladding material made up of multiple welded plates, the cladding welds must be examined over the full length either use radiography or ultrasound prior to bonding the cladding to the base material. The welding must be performed by an authorized manufacturer and a partial data report supplied if not done by the vessel manufacturer.

When any part of the cladding of an integrally clad plate is used in the thickness calculation, the clad plate must show a minimum shear strength of 140MPa (when tested as described in the specification). One shear test per plate is required. Weld metal overlay does not require any shear tests.

Ultrasound examination of the bond between the base plate and cladding is performed in accordance with the requirements of SA-578 to acceptance level B or C. Acceptance level B requires areas of interfacial de-bond or discontinuity be confined to a circle of with a diameter 75mm or $\frac{1}{2}$ the plate thickness, whichever is greater. It similarly requires adjacent discontinuities to be separated by the greatest diameter of the larger discontinuity (unless they are confined with the circle defined previously. Acceptance level C requires all discontinuities be confined to a 25mm diameter circle.

When including the cladding thickness in the strength calculation, the integral clad plate or base plate along with metal overlay clad base metal must meet requirements of Section VIII Div. 2 Part 3. If integrally clad plate is used, it must meet one of the specific specifications: SA-263, -264, or -265 which for practical purposes correspond to ASTM-A263, -A264, and -A265. The base material must consist of base plate listed in one of the material tables of Part 3 of VIII-2.

5.2 Part 4 - Thickness in design calculation excluding the cladding

Design calculations for clad plate other than the three specification listed above, the base material must conform to the requirements of VIII-2 Part 3 and the clad (either integral or weld overlay) must meet the requirements of VIII-2 (6.5). Weld qualifications are done per VIII-2 (6.5.3) which refers to Section IX.

5.3 Part 5 - Design by analysis considerations

Unlike Div.1 or Div. 2 Part 4, Part 5 relies purely on stress analysis and has no geometry based rules. Part 5 lends itself well to stress analysis by Finite Element Analysis (FEA). Part 5 analysis must pass the following cases:

1. Protection against plastic collapse (three alternative methods)
 - a. Elastic Stress Analysis-Stress Categorization
 - b. Limit-Load Method
 - c. Elastic-Plastic Stress Analysis
2. Local failure
3. Buckling (when compressive loads exist)
4. Cyclic loading

For analysis by Part 5, the cladding is explicitly considered. When using FEA, the base metal and cladding are explicitly meshed and assigned the respective material properties.

For elastic analysis, stress is categorized, i.e. into primary and secondary bending and membrane stresses. For continuum elements, Stress Classification Lines, SCL (Figure 12-3) are used to linearize the stress into bending and membrane components. Clad vessels possess a material discontinuity (e.g., base metal with cladding). When the cladding is included in the strength calculation, the SCL should include all materials and associated loadings. If one of the materials, such as cladding, is neglected for strength calculations, then only the base metal thickness should be used to calculate the membrane and bending stresses.

Table 5.6 Annex 5C classifies cladding stress resulting from differential expansion as peak stress for both membrane and bending stresses (doesn't contribute to deformation). Thermal stress due to cladding material with a coefficient of expansion that differs from that of the base material is classified as local stress.

5.4 Clad tubesheets

For tube-to-tubesheet welds to be considered as strength welds, Section 3.3.7 requires that the welds are designed in accordance with Section 4.18.10 which defines full and partial strength welds.

When the welds are made to integral clad, shear testing (following SA-263) and ultrasonic inspection (SA-578 including Supplementary Requirement S1) are required. Ultrasound acceptance criteria is given in SA-263 Quality Level Class 1 is to be used. Tube-to-tubesheet welds into integral clad failing to meet either the shear testing or ultrasound inspection requirements cannot rely on the connection between the tube and clad.

5.5 Special requirements for clad or weld overlay linings and lined parts

Section 6.5 requires:

1. Cladded materials must be post weld heat treated when it is a requirement of the base material. PWHT is based upon base material thickness.
2. Any inserted strips used to restore cladding at joints must the same thickness of the clad material and backed with corrosion resistant weld material in the groove in order to maintain a surface flush with the adjoining cladding surfaces.
3. Weld material corrosion resistance not substantially less than the cladding and it is recommended that it deposit weld metal of practically the same composition of the cladding. Different composition is allowed if it has better mechanical properties.
4. Welds must be done in accordance with Section IX.
5. Joint type and weld procedure must be selected to minimize the formation of brittle weld composition that may result from the mixture of the base and clad alloys.
6. In welding corner joints, base material must be removed or weld process used that ensure fusion of the base materials.
7. Caution is given about the potential for stress concentrations resulting from differing thermal expansion under extreme thermal conditions. In particular, cyclic thermal loading may create cracking in cladding and this should be looked at even if the cladding is not used in the thickness calculation.

6 Section III

6.1 Div. 1 Subsection NB

Section III Div.1 Subsection NB specifies clad components as constructed using materials in II-Part D Subpart 1, Tables 2A and 2B. III-NB does not allow any credit for structural strength of cladding and the cladding is not included in the primary stress calculations (Mandatory appendix XIII-3100). Material thickness is based solely on the base material and ignoring the additional thickness provided by the cladding. The cladding thickness is considered with regard to peak and secondary stresses (satisfying Mandatory appendix XIII-3400 and -3500) with respect to thermal analysis and the stress analysis where stresses must be limited to values prescribed in XIII-3400, -3500. For integral cladding where thickness is less than 10% of the total component thickness, this check for secondary and peak stress is excluded. Cladding material is considered in bearing strength calculations.

Welding material used for overlay cladding is exempted from strictly following Section IX. However, chemical analysis of test welds follows Section IX, QW-214.1, and removal of chemical samples follows Table QW-453. Delta ferrite determination is not required. Provision for cladding repair by welding is given. Guidance is given that joint types for welding clad components need to be selected such that they prevent the formation of brittle weld composition.

Internal structural supports must be welded to the base metal except for weld overlay cladding. Brazing may be used to attach cladding to base material and tubes to tube sheets within certain restrictions that apply to brazed joints in general.

When cladding is applied over welds, weld inspections must occur prior to the application of weld overlay cladding. Weld metal cladding is examined by liquid penetrant examining for liquid bleeding at the surface. Leaks coming from incomplete base metal bond are not considered relevant during inspection. Welds exposed to corrosive action should have resistance similar to that of the cladding.

6.2 Div. 5 Subsection HB, Subpart B

The construction rules for “pressure boundary metallic components” in nuclear reactors under elevated temperature cyclic service are provided in Section III, Div. 5 Subsection HB, Subpart B.

6.2.1 Permitted Material Specifications.

Clad component where the cladding is greater than 10% of the thickness of the base material shall conform to the requirements of one of the specifications for material given in Section II, Part D, Subpart 1, Tables 2A, 2B, and 4, including all applicable footnotes in the table.

For cladding which is 10% or less of the thickness of the base material, conformance to the material specifications in Section II, Part D, Subpart 1, Tables 2A, 2B, and 4 is not required. Thus, non-Code qualified materials can be used for cladding if this thickness exception is satisfied.

6.2.2 *Design Rules.*

Limited design rules for cladding are provided in Section III, Division 5, Subsection HB, Subpart B, paragraph HBB-3227.8 Cladding.

- a) *Load-Controlled Stresses.* No structural strength shall be attributed to the cladding in satisfying the load controlled stress limits in HBB-3200.
- b) *Design Dimensions.* The dimensions stipulated in 1) and 2) below shall be used in the design of the component.
 - 1) For components subjected to internal pressure, the inside diameter shall be taken at the nominal inner face of the cladding.
 - 2) For components subjected to external pressure, the outside diameter shall be taken at the outer face of the base metal.
- c) *Deformation-Controlled Quantities.* No structural strength shall be attributed to the cladding in satisfying requirements on buckling instability. However, the cladding shall be considered in all other calculations related to satisfying limits on deformation-controlled quantities.
- d) *Bearing Stresses.* In satisfying (a), the presence of cladding shall be included.

The above Section III code rules for cladded structural components in elevated temperature service have been assessed by the ASME Code Committees (Working Group on High Temperature Liquid-cooled Reactors and Subgroup on Elevated Temperature Design) as delinquent in several areas. Most notably in Paragraph HBB-3227.8(d) where it requires that the cladding shall be considered in calculations related to limitations on deformation controlled quantities, i.e. cyclic loading, but does not provide guidance or requirements for that assessment. Thus applicable design rules will need to be developed to support the design and construction of these cladded components for molten salt reactor applications.

7 Testing requirements, inspection requirements, and material properties of interest

7.1 Material properties

Depending on the ASME code section followed and the path through the code, the material properties needed to perform the analysis include the following:

1. Allowable stress of cladding material
2. Coefficient of thermal expansion (for consideration only)
3. E, Poisson's ratio, stress-strain curve parameters, cyclic stress strain parameters

7.2 Testing requirements

1. When taking credit for cladding thickness in design thickness calculation:
 - a. Shear testing required on integral clad sheets (see Figure 12-4)
 - b. Corrosion allowance on cladding must be removed before tension tests
2. Pressure test of lining with visual post inspection of liner looking for seepage through liner joints.
3. Welding guided bend test-visual inspection of cracks

For bend tests on weld overlay cladding, the code prescribes that there should be no open discontinuity exceeding 1/16 in. (1.5 mm), measured in any direction in the cladding, and no open discontinuity exceeding 1/8 in. (3 mm) along the approximate weld interface. (ASME, 2017)

The weld overlay interface profile perpendicular to the direction of weld travel should be nearly straight and free of "spikes" of base metal between weld passes in order to reduce weld cracking. Side bend test checks for this.

8 Piping

Cladding is also addressed in the piping codes, ANSI/ASME B31.1 Power Piping and ANSI/ASME B31.3 Process Piping. The rules for B31.3 follow closely the rules for VIII-1 whereas B31.1 does not allow the inclusion of cladding for thickness calculation under any circumstance.

8.1 ANSI/ASME B31.1

Materials with cladding or lining may be used if:

1. Base material is an approved code material (base metal determines the allowable stress at design temperature)
2. Cladding material is appropriate (as determined by the user) and method of application does not detract from the base material.
3. Allowable bending operations are only those that do not damage or detrimentally thin the cladding
4. Prescribes welding and inspection in Chapt. V and VI of B31.1 which ultimately refer to ASME BPVC procedures.

No credit with regard to the cladding thickness is allowed in the determination of structural strength.

8.2 ANSI/ASME B31.3

The code rules for pressure piping are similar to those of VIII-1. When using one of the ASTM cladding specifications: ASTM A263, A264, A265, the cladding thickness is included in the calculation on the condition that:

1. both the base and clad are acceptable code materials, and
2. the clad plate has been shear tested and meets all of the shear test requirements as specified in the ASTM specification.

Otherwise, only base material thickness is used. B31.3 does not cover deterioration in service and references Section VIII for manufacturing and inspection. Allowable stresses are based similarly on the methods used in VIII-1. The code notes that cladding stress allowable cannot exceed the base material. However, unlike VIII-1, the code does not provide explicitly the manner to include the cladding in thickness calculation such as shown in equation (4-1).

9 Comments on Fabrication

High forming strains can make certain materials prone to SCC. This includes 300 series SS. (BP, 2006). BP requires minimum cladding thickness of 3mm with other approval (BP, 2006). The application of the weld material even after post weld heat treatment (PWHT) results in residual stresses. This is due to the generally different coefficients of thermal expansion between the cladding and base material. In one study using the finite element analysis (FEA), residual tensile stresses of 400MPa remained in the cladding (Nishikawa, Katsuyama, & Onizawa, 2009).

9.1 Welding

Weld overlay cladding is most commonly performed using submerged arc welding (SAW). SAW and ESW are most economical for large areas.

Typical processes include electroslag arc welding (ESW), SAW, SMAW, gas tungsten arc welding (GMAW or MIG), strip overlaying, and similar techniques. ESW overlaying or SAW strip overlaying techniques should be used for large surface areas whilst hot wire gas tungsten arc welding (GTAW or TIG) should be used for precision components. SAW wire or SMAW processes may be used for intermediate areas. The use of GMAW or flux-cored arc welding (FCAW) processes shall be subject to BP approval (BP, 2006).

One of the main concerns for weld overlay cladding added by arc welding is dilution or change in the chemistry of the added material through mixing with the base metal. Dilution of the cladding can affect the bond integrity along with resistance to hot cracking or corrosion. ASME BP&V code section IX provides prescriptions on qualification methods to limit this issue.

The ASME BP&V code references difficulties that have been experienced in welding materials differing greatly in chemical composition. Mixtures of uncertain chemical composition and physical properties are produced at the line of fusion. Some of these mixtures are brittle and may give rise to cracks during solidification or afterward. To avoid weld embrittlement, special care is required in the selection of lining material and welding electrodes, and in the application of controls over the welding process and other fabrication procedures.

9.2 Explosive Bonding

Explosively bonded welds can create 100% joint efficiency. The resulting interface is essentially the same as bulk component materials (Westinghouse Electric Corporation, 1972). Explosive bonding is most commonly used for joining flat plates or concentric cylinders. Main requirement for joining materials is that they have sufficient ductility (>10%) and fracture toughness (> 30 J) to endure the rapid deformation associated with the joining process. (Davis, 1994)

10 Nuclear Experience

Light Water Reactors (LWRs) have been operating successfully for decades using cladded reactor pressure vessels – typically stainless steel cladding on low-alloy reactor pressure vessel steel. Some experience on other clad components in LWRs is described below.

The steam generators at Carolina Power & Light H. B. Robinson No. 2 plant were fabricated with explosively clad tubesheets. The primary coolant boundary consisted of carbon steel coolant channel, clad with austenitic stainless weld deposit material. Westinghouse used the Detaclad process for explosion bond. The procedure for explosively bond clad sheet was developed in 1964 at which time Westinghouse converted to this process from weld overlay. The method was preferred from the standpoint of making the tube-to-tubesheet welds.

Local overheating of partition plate weld area during weld of the primary channel head to tubeplate causing cladding separation at the tubelane. Cladding failures occurred due to large forces being imparted on cladding during cooling after PWHT.

Clad separation at the tube-to-tubesheet weld in tubes adjacent to the partition on the primary side. Ultrasonic examination of all clad tubesheets revealed additional areas of cladding separation. Due to the multiple failed inspections, the cladding in the tubelane was removed and manual weld overlay was applied. In late 1970, Tampa switched to Plasma weld overlay of for quality Control at facility (Westinghouse Electric Corporation, 1972).

The report noted that at the time of writing the report, no instance of tube-to-tubesheet weld failure had been observed in the Westinghouse plants in operation in which weld cladding had been used. (Westinghouse Electric Corporation, 1972).

11 Gap analysis:

The ASME and ANSI codes address cladding sufficiently well for industry needs. For application in nuclear space, there are areas that may require additional effort. It is noted that the B31.1 power piping code which is used in nuclear applications does not allow the use of cladding in thickness calculations nor does Section III NB of BPVC.

The code provides no guidance on corrosion rates or material capability and only requires that an appropriate corrosion allowance is provided.

The most extensive analysis is provided in VIII-2 Part 5 which is geometry independent and allows analysis of all areas. In this regard, issues like stress resulting from thermal expansion mismatch of the cladding can be analyzed. However, there is little guidance on how to go about this analysis. Similarly, there is no mention of analyzing the interface strength of the cladding. Interface strength is addressed through the required shear tests of the integral clad plate and through welding tests and procedures. Creep fatigue is not covered.

Noting the design rules here focus on VIII, the materials suitable for the associated analysis rules are limited to those materials already listed for use with VIII and with the associated temperature ranges.

Japanese codes include no specific provision related to accounting for the residual stress that results in weld overlay cladding (Nishikawa, Katsuyama, & Onizawa, 2009). This is also not explicitly covered in ASME codes.

No analysis is needed when cladding is not considered. However, cyclic thermal loading may create cracking in cladding and this should be looked at even if the cladding is not used in the thickness calculation. This is not explicitly addressed outside of a caution.

The current nuclear design rules for clad components under elevated temperature service have identified deficiencies. Applicable design rules will need to be developed to support the design and construction of these clad components for molten salt reactor applications.

12 Figures

Figure 12-1. Flow chart for Section VIII Div. 1.

Figure 12-2. Flow chart for Section VIII Div. 2.

13 Summary

The design and use of corrosion resistant weld overlay and integral claddings for pressure use in industry is generally covered by Section 8 of the ASME BPVC, ANSI B31.1 Code for Power Piping, and ANSI B31.3 Code for Pressure Piping. The cladding can be either integral clad plate produced by explosion bonding or applied through weld overlay. ASTM provides a standard for integrally clad plate. All the codes point to ASME BP&V code section IX for weld fabrication procedure and inspection requirements.

Within Section VIII of the BPVC, there are multiple paths through analysis. The main variations through the design paths are rule based versus analysis based. In the case of rule based, the paths offer differing rigor and design margin. In all cases, one can choose to include the cladding thickness in the design thickness calculation. When the cladding thickness is required, the code limits the cladding material specifications and dictates fabrication and inspection requirements. When including the cladding thickness, the main differences in paths are the analysis rigor and design margin whereas the fabrication and inspection requirements are generally identical. ANSI B31.3 follows closely the rules of VIII-1 whereas B31.1 does not allow inclusion of the cladding thickness.

An example of cladding failure in the nuclear industry for light water reactor (low temperature) was discussed and a discussion of gaps in the design rules when looking to apply these rules to nuclear applications is included.

The guidance for nuclear components under elevated temperature service as provided in Section III, Division 5 has been deemed insufficient and applicable design rules will need to be developed to support the design and construction of these clad components for molten salt reactor applications.

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