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Cladding of Pressure Vessel Steels for Coal Conversion Applications — A Literature Review

D. P. Edmonds

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METALS AND CERAMICS DIVISION

CLADDING OF PRESSURE VESSEL STEELS FOR COAL CONVERSION
APPLICATIONS — A LITERATURE REVIEW

D. P. Edmonds

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APPLICATIONS — A LITERATURE REVIEW

D. P. Edmonds

ABSTRACT

This paper reviews the available literature concerning corrosion-resistant lining of large ferritic steel vessels and piping, applicable to coal gasification and liquefaction systems. Potential ferritic steel pressure vessel and piping materials are discussed along with potential stainless steel and nickel-base cladding materials. The various lining techniques currently used in the United States and abroad are also reviewed, with advantages and disadvantages of each. Finally, materials problems with the various techniques are described.

Several methods are available to produce ferritic steel components lined with corrosion-resistant layers. For low-temperature-low-thermal cycling applications, applied linings may be a good choice. However, for more critical applications, integral cladding is generally preferred. Integral cladding may be performed by a variety of methods, including solid state cladding, braze-bond cladding, and weld overlay (fusion) cladding. The lining process should be chosen after careful consideration of base metals and cladding metals desired and of the service requirements for the lined component.

1. INTRODUCTION

With the present energy dilemma in this country, much emphasis is being placed on the development of new energy resources and the expansion of present resources. With today's technology, one of our most plentiful and usable natural resources is coal. However, a large percentage of the available coal contains relatively high sulfur and ash concentrations. Utilities are facing significant problems with present coal-fired boilers because of pollutants formed from the sulfur and ash, and either low sulfur and ash content coals or expensive pollution control devices must be used. Another method of utilizing the coal is to convert it to a combustible liquid or gaseous form that is easily transported. Several advanced coal conversion schemes are being developed and tested today that not only convert the coal but also remove the sulfur and ash from the product.

Coal conversion systems of interest here can be grouped into at least two major categories: coal gasification and coal liquefaction. Both processes generally take place at relatively high temperatures and pressures and create very aggressive environments. Large differences in operating temperatures and pressures exist between the various systems, with liquefaction systems generally operating at lower temperatures and higher pressures than gasification systems. Temperatures greater than 1150°C (2100°F) for gasification systems and pressures up to 31 MPa (4500 psi) for liquefaction systems are being considered. Atmospheres that are very corrosive and erosive exist in reaction vessels and associated piping, whereas very abrasive conditions exist in the coal feed systems.

Proposed reaction vessels vary from small to very large sizes with diameters up to 18 m (60 ft) and lengths to over 61 m (200 ft). Design and fabrication of these vessels is according to ASME Boiler and Pressure Vessel Code, Sect. VIII, Div. 1 or Div. 2 rules.¹ Size and weight limitations of shop fabrication and shipping facilities will make field fabrication necessary for many of these vessels. However, whether shop or field fabricated, the design of these vessels will present a number of fabrication challenges.

The elevated design temperatures and pressures of these systems require vessel wall thicknesses of 20 to 35 cm (8 to 14 in.). Pressure vessel materials not only must withstand the temperatures and pressures, but also must be resistant to the aggressive environments during operation and shutdown. The proposed thicknesses and sizes make it economically prohibitive to fabricate the vessels out of solid, corrosion- and erosion-resistant materials. As a result, the reaction vessels are generally being designed using common pressure vessel (ferritic) steels, lined with corrosion-resistant materials. Ceramic lining is also being considered for many of the vessels.

Several techniques are available for achieving a corrosion-resistant lining in reaction vessels and associated piping. These can be grouped into two general categories: applied lining and integral cladding. Applied linings consist of sheet, strip, or plate that is intermittently attached to the vessel or piping by acceptable welding processes. Integrally clad components, which have the clad continuously bonded to the base metal, are commonly produced by joining processes that can be broken into three categories: solid state welding, fusion welding, and braze bonding. These categories of lining are used for a variety of applications, and each has specific advantages and disadvantages.

Reviewed here is the available literature concerning corrosion- and erosion-resistant lining of large vessels and piping used in coal gasification and liquefaction systems. Potential ferritic steel pressure vessel (SA-533 grade B class 1; SA-387 grade 22 class 2; and SA-516 grade 70) and piping materials are discussed along with potential stainless steel and nickel-base cladding materials. Advantages and disadvantages of these materials and cladding processes are also discussed.

2. BRIEF HISTORY OF CLADDING

Cladding of carbon and low-alloy steels with corrosion-resistant materials has been performed commercially since the early 1930s. Early cladding processes were generally limited to solid state bonding and casting techniques.² Using the solid state techniques, plates of backing steel and cladding metal were cleaned and stacked together. Usually more than one plate was clad simultaneously, and parting compounds were placed between adjacent clad plates to prevent bonding. This assembly was then heated to an appropriate temperature and placed in a large press or clamped tightly together for a time sufficient for bonding to occur. This process was soon modified to use rolling instead of pressing or clamping. The roll-cladding method is still important throughout the world. The casting techniques generally use plates or sheets of the cladding metal placed vertically in a mold with the backing steels cast around them. This process has received considerable attention in the U.S.S.R. but has had little use in the United States because of "insurmountable production difficulties."³

A few years later, cladding by welding became popular. Gas and arc welding techniques were used to overlay backing steels with corrosion-resistant metals. Automated processes were preferred and were commonly used in the early 1950s.⁴ Also common was a process termed intermelting that involved electroslog melting of cladding metal to a backing steel.⁵ The solid state bonding and casting methods, though, still remained the primary methods used because of the slow speeds of the weld cladding processes. It was not until the middle 1960s that higher-deposition-rate weld overlaying processes began to be developed and used widely.

Many different methods of cladding have been developed and are discussed in the literature today. However, only about one-half of those processes reported are used commercially to produce significant amounts of materials.⁶ This review deals only with the cladding processes commonly used in the United States: applied linings, roll-bond cladding, explosive cladding, weld overlay cladding, and braze cladding.

3. CLADDING PROCESSES

3.1 General

Several methods are available for lining ferritic steel vessels and piping with corrosion-resistant material. These methods can be grouped into two general categories: applied linings and integral cladding. The ASME Boiler and Pressure Vessel Code accepts both categories of lining.¹

3.2 Applied Linings

Applied linings consist of plates, sheets, or strips of corrosion-resistant materials intermittently attached to the structure by welding. This type of lining is commonly used for applications in the process industries, including the chemical, petrochemical, oil refining, paper, and mining industries.⁷ A variety of materials and product forms can be used to line components by this method. Essentially any weldable grade of corrosion-resistant material can be applied.

Lining of vessels or large piping can be done either before or after plate forming. Attachment of the liners is done by a variety of welding processes. When narrow strips are used, welding is ordinarily done only at the edges. When larger sheets or plates of liner material are used, attachment between the edges is generally required, which is accomplished by spot, seam, or plug welding.⁷ Spot welds can be made using any one of several welding processes: gas tungsten-arc, gas metal-arc, or resistance. Seam welds are usually made by the resistance welding, submerged-arc welding, or gas metal-arc welding processes. Plug welds are made by filling predrilled holes in the liner with weld metal using any of the fusion welding processes where filler metal is added. Another method of producing lined product is to build a separate liner from the corrosion-resistant material to fit the internal contour of the component. This liner is then slid into place and attached by one of the methods mentioned above.

Almost any weldable grade of corrosion-resistant material that is available in sheet or strip form can be applied as a lining. In general, larger sheets of liner material can be applied in shop fabrication than in field fabrication. Sheet liners in thicknesses ranging from 1.6 to 4.8 mm (0.06 to 0.19 in.) are commonly used with widths from 0.6 to 1.2 m (4 to 48 in.)² and lengths from 0.9 to 3.6 m (3 to 12 ft).⁸ Strips in widths from 0.05 to 0.2 m (2 to 6 in.) and lengths from 0.6 to 1.0 m (24 to 40 in.) for field-applied liners and 0.6 to 3.0 m (24 to 120 in.) for shop-applied liners are also used. For higher temperature applications, narrower strips are customarily used.⁸ Because of the differences in coefficients of thermal expansion that usually exist between the liner and base metal, the wider spacings can lead to buckling of the liner during exposure at elevated temperatures. Repeated buckling can lead to fatigue damage in the liner, welds, and heat-affected zones (HAZs).

Care must be taken to choose welding processes and filler metals that produce sound welds between the liner and the base metal. The ASME code (Sect. VIII) requires that "the type of joints and welding procedure shall be such as to minimize the formation of brittle weld composition by the mixture of metals of corrosion resistant alloy and the base material."¹ Cracks in these welds could allow leakage of corrosive vessel contents through the lining, subsequently causing degradation of the load-bearing capabilities of the component. Also, the composition of the weld metal should be as close to the composition of the liner material

as possible, for if weld metals with significantly lower corrosion resistance are used, galvanic action and accelerated corrosion of the weld can occur. The ASME code allows only weld metals of equal or greater corrosion resistance than the liner materials.¹

Surfaces to be lined should be clean (suitable cleaning methods include pickling, sand blasting, and wire brushing) and free of scale. Joints between two pieces of liner material should be spaced far enough apart to permit sound welding to the base metal yet close enough together that large volumes of weld metal are not required. Overlapping strips (or sheets) and inserted strips of the weld joint are sometimes used so that the mixed weld metal (ferritic base metal and cladding metal) will not be exposed to corrosive environments.

The ferritic base metals should be treated with the same care during liner welding as during welding of the primary-pressure boundary joints. Dry, low-hydrogen electrodes should be used with recommended preheat and postweld heat treatments (PWHTs) to minimize the tendency for cold cracking (hydrogen-delayed cracking) in the ferritic steel HAZs. It should be pointed out that the recommended PWHTs for the ferritic steel base metals sometimes fall within the temperature range for austenitic chromium-nickel stainless liner materials in which sensitization and sigma phase formation can occur. Therefore, liner materials should be selected with the temperature requirements for the PWHT in mind.

3.3 Integral Cladding

Integrally clad materials are "composites of two or more metals joined in a continuous manner by a metallurgical bond."⁹ Continuously bonded clads are more desirable than applied lining in meeting the severe requirements of components operating under cyclic temperature and pressure conditions. Methods for producing integrally clad components can be grouped into three categories: solid state welding, braze bonding, and fusion welding. The major methods of producing integrally clad components are discussed in this section.

3.3.1 Solid state cladding

Solid state welding is defined as "a welding process wherein coalescence is produced essentially at temperatures below the melting point of the base metals being joined, without the addition of a braze filler metal. Pressure may or may not be used."¹⁰ Two solid state processes, roll bonding and explosive welding, are used to produce clad plate or components. These processes use pressure and depend on diffusion at the clad interface to produce bonding.

3.3.1.1 Roll cladding. Roll-clad plates and sheets are produced by hot rolling a welded assembly that consists of a carbon or alloy backing

steel and a corrosion-resistant cladding material. Roll cladding is the most widely used method for producing clad plate in Europe¹¹ and has wide use in the U.S.S.R.³ Two American steel manufacturers also produce significant quantities of roll-clad plate of sizes usable in pressure vessel and piping fabrication. The use of roll-clad plate is generally decreasing with the advent of the newer, higher-deposition-rate weld cladding processes.

Two conditions necessary for solid state bonding are heat and pressure. For bonding of carbon or alloy backing steels to conventional cladding materials (stainless steels, nickels, high-nickel alloys, and copper-nickel alloys), rolling temperatures from 1000 to 1300°C (1800 to 2400°F) are typically used.^{12,13} Pressure is applied from the rolls and is dependent on roll diameters, percent reduction of thickness, and yield strengths of the backing steel and cladding materials. If the yield strengths of the two materials differ significantly, large reductions are required to produce bonding. Through several investigations, the effects of temperature and percent reduction on bond strength for a variety of materials have been determined and formulas for predicting these effects have been developed.¹⁴⁻¹⁹ Therefore, the necessary rolling temperatures and percent reductions for producing a desired bond strength between two materials can be predicted, with higher temperatures and reductions producing higher bond strengths.

Another necessary condition for solid state bonding is that the two surfaces be brought into intimate contact. Absorbed gases and oxides on the mating surfaces increase the difficulty of obtaining this contact.²⁰ The surfaces must therefore be cleaned and kept clean until roll bonding is completed. Cleaning methods most often used include ultrasonic cleaning, grinding, shot blasting, anodic-acid pickling, machining, wire brushing, hydrogen reduction, or combinations of these.²¹ Surfaces are then protected from the atmosphere by applying a thin layer of nickel or iron to the clad mating surface, by seal welding the materials together immediately after cleaning, by using atmospheric control furnaces for heating, or by employing combinations of these methods.

Cladding alloys that contain chromium, aluminum, or silicon form tough, hard, adherent, continuous oxides on their surfaces.⁶ Oxides that form on the backing steels are generally not as tough as those on the cladding materials and tend to break up more easily during rolling. Thin interlayers of iron or nickel are applied to the clad metal by a variety of methods: weld deposition of a thin layer of iron or mild steel (Colclad²² and Ingersol²³ processes), thermal spraying of nickel,²⁴ electrolytic nickel plating [thicknesses between 0.025 and 0.0025 mm (0.001 and 0.0001 in.)], and gas metallization. For production of very thick plates, the iron or mild steel coatings are generally used because lower reductions are required for bonding. However, an interlayer of nickel is significantly more effective than the iron or mild steel coatings in preventing diffusion of carbon into the cladding.²⁵

Production of roll-clad plate is most often done using a "sandwich pack" method (Fig. 1), whereby two or more steel plates are clad simultaneously.²¹ Materials are prepared using the above methods, stacked together, and seal welded around the periphery. Parting compounds or separating plates are placed between adjacent clad plates to prevent bonding. In some processes a "getter" is introduced into the pack to absorb trapped gases.²¹ The complete package is heated to rolling temperature and hot rolled. The plate edges are then sheared or flame cut, the clad plates are separated, and necessary heat treatments are performed.

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(a) TWO-LAYER SANDWICH PACK

(b) MULTILAYER SANDWICH PACK

Fig. 1. Schematic of roll cladding process.

The dimensions and weights of roll-clad plate that can be produced have increased in the past few years as a result of both special soaking furnaces that heat plates in the vertical position and larger rolling

mills. Several maximum plate widths are available:²⁶ Lukens, United States, 4.5 m (14.8 ft); Stinox, France, 3.5 m (11.5 ft); Phoenix-Rheinrohr, German Federal Republic, 4.0 m (13.1 ft); and Colville, England, 3.4 m (11.2 ft). Plate lengths vary up to 16 m (52 ft). Plate thicknesses usually vary up to 100 mm (4 in.), except for maximum thicknesses of 250 mm (10 in.) from Phoenix-Rheinrohr. The cladding layers typically account for 5 to 40% of the total thickness of the plates.

If thermal expansion coefficients of the cladding and backing steel differ significantly, problems can be encountered during hot rolling. Bowing, weld breakage, and clad separation can take place unless special precautions are taken.²³ As a result, large areas of insufficient bond have been found in some roll-clad plate.²⁷ Another disadvantage of the roll-clad process is that the large reductions of thickness usually required to produce bonding limit the plate thicknesses available and make the production of thick plates very difficult. Also, prolonged heating of roll-clad plates in the 800 to 1300°C (1472 to 2372°F) range during hot rolling and subsequent hot forming makes them more susceptible to carbon diffusion from the backing steel to the clad.²⁸

Roll-clad plates decrease the amount of welding equipment and manpower required by a pressure vessel or piping manufacturer. Also, roll-clad plates simplify production of clad components, such as pressure vessel heads, nozzles, and large pipe and fittings, that are difficult to weld overlay because of their irregular shapes.

3.3.1.2 Explosive cladding. Explosive welding is a solid state process also used for cladding. Pressure is obtained from an explosion occurring above the cladding material, and heat is generated because of large deformations at the interface of the cladding material and backing steel. Attempts were first made in the 1940s to use explosive energy for welding.²⁹ However, it was not until 1963 that the first facility was constructed in the United States for producing explosive clad products.

Explosive bonding is done by detonating an explosive charge above two materials to be bonded (Fig. 2). Surface grinding is usually performed on the mating surfaces before bonding. The backing plate is generally placed against an anvil, which can be the ground, a large bedrock, sand, etc. A layer of explosive is then placed above the entire surface of the cladding metal and is detonated at one end or at the center of the work. The shock wave propagates at a velocity of 4000 to 5000 m/sec (13,000 to 16,000 ft/sec) (Fig. 3).³⁰ The cladding plate, which is separated from the backing plate by a small distance, is accelerated by the shock wave pressure. An angle is established between the deflected and undeflected materials that is dependent on cladding conditions. When cladding conditions are correct, high pressures are generated between the workpieces, and a high-velocity jet is formed ahead of the colliding region.³¹ Jet velocities greater than 7000 m/sec (23,000 ft/sec) have been reported by E. I. du Pont Nemours & Co. Oxides and impurities on the surfaces are

Fig. 2. Schematic of explosive cladding process.

Fig. 3. High-velocity jet in explosive clad due to upstream pressure.

squeezed out of the interface and carried away in the jet. Though the configuration of the interface after cladding depends on the cladding conditions, it is normally wavy in nature. After cladding, plates are flattened to desired tolerances.

Several variables that must be controlled to produce uniform and reproducible clads are (1) detonation forces and velocities, (2) type and thickness of explosive, (3) plate thicknesses, and (4) standoff distances (plate separation).³² Standoff distances of 2.4 to 6.4 mm (0.09 to 0.25 in.) are common for cladding. Nonuniform standoff distances and/or explosives can produce inferior products. Too much deformation during cladding can cause excessive melting at the interface, which, with certain combinations of materials, can lead to the formation of brittle intermetallics and degradation of the bond strength.

A variety of clad materials can be produced by this process.³³ Stainless steels, nickel and nickel alloys, copper and copper alloys, titanium, and tantalum can be clad onto carbon and low-alloy backing steels. In addition to production of clad plates, explosive bonding is used for a variety of other cladding applications, as in the cladding of formed parts (vessel shells and heads), nozzles, and tube sheets.³⁴

In general, it is felt that explosion cladding is not economical for clad materials that can be produced by roll bonding.³⁵ Also, cold deformation of the backing steel usually makes heat treatment necessary before construction of critical components. There are, however, a number of advantages to explosion cladding.³⁰ It is possible to produce explosive clad products such as titanium on steel that are not possible with most of the other processes. A variety of sizes and thicknesses can be clad because the process does not involve machinery that would limit the dimensions of the product. Cladding metals up to 2.4 cm (1 in.) thick, backing steels up to 45 cm (18 in.) thick, and surface areas up to 19 m² (205 ft²) have been bonded commercially. Also, cladding occurs over a very short period of time, and the bulk material is not subjected to high temperatures. Therefore, diffusion across the clad interface during bonding is significantly lower in explosive cladding than in hot rolling.

3.3.2 Braze-bond cladding

Braze bonding is another method for producing large, integrally clad plates.³⁶ A proprietary vacuum-braze process is claimed to produce clads with 100% bond. One or more plates can be clad at the same time³⁶ (Fig. 4). A sandwich structure is generally used with a compatible braze metal preplaced between the base metal and the cladding metal. A vacuum is drawn on the fraying surfaces to eliminate contamination. The assembly is then heated and pressed together, which not only melts the braze alloy but also relieves stresses within the base steel.

Because this is a proprietary process, very little information is available in the open literature. Braze-clad materials are not as common as weld-overlayed or solid state clad materials. However, braze cladding is of considerable commercial importance since it is applicable to a variety of materials and products (plates, pipes, rings, forgings, and curved surfaces).³⁶ Combinations of cladding and base metals that are not compatible with weld cladding processes can often be joined using this technique. Changes in base-metal structures due to extended heating and difficulties with welding braze-clad plates are the major disadvantages of this process.

3.3.3 Weld overlaying

A common method for producing sound integrally clad components is by fusion welding (weld overlaying). The fusion welding processes can

Fig. 4. Schematic of vacuum brazing process for producing clad plates.

be divided into two general categories: consumable-electrode processes and nonconsumable-electrode processes. The consumable-electrode cladding processes include submerged-arc, shielded metal-arc, gas metal-arc, and flux cored-arc welding. The nonconsumable-electrode cladding processes include gas tungsten-arc and plasma-arc welding. Large quantities of clad materials are produced each year by these processes. Oxyacetylene welding is often used for hardfacing. It is not, however, generally used for cladding with corrosion-resistant materials and will not be discussed here.

Much published information is available for the weld overlay processes, and many new innovations have significantly increased their use in the past 15 years. Modifications to the basic processes have significantly increased clad-metal deposition rates and welding speeds. For instance, the submerged-arc process was originally used for cladding using one filler wire. The process was modified later to accommodate two and three filler wires fed simultaneously and, more recently, to feed six wires or a wide strip. These modifications have greatly decreased the time necessary to weld overlay components.

Most of the recent literature is concerned with submerged-arc cladding using strip electrodes. However, several articles discuss weld overlaying by "hot-wire" gas tungsten-arc and plasma-arc welding. Two publications review weld overlaying in Europe: *New Trends in the Development of Clad Plate* by M. Zidek (Czech)¹² and *Review of Overlay Welding Procedures for Light Water Reactor Pressure Vessels* by T. G. Gooch (Welding Institute).³⁷ This section covers many of the topics discussed in these two publications.

3.3.3.1 Consumable-electrode overlaying. The consumable-electrode overlaying processes use the welding filler metal as the electrode, with an arc established between the base metal and the filler wire. The filler metal is fed continuously into the weld pool to maintain constant arc voltages, while the molten weld pool is protected from the atmosphere either by a shielding gas or by refractory slags. Detailed discussions of these processes are given in the following sections.

Submerged-arc cladding. The submerged-arc (SA) process is defined by the American Welding Society (AWS) as "an arc welding process wherein coalescence is produced by heating with an arc or arcs between a bare metal electrode or electrodes and the work. The arc is shielded by a blanket of granular, fusible material on the work. Pressure is not used and filler metal is obtained from the electrode and sometimes from a supplementary welding rod."³⁸ A schematic of the process is shown in Fig. 5. It is one of the most widely used fusion welding processes for cladding. Cladding can be done either automatically or semiautomatically. Welding operators generally like the process because there are relatively few variables to maintain and there is no open arc.

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Fig. 5. Schematic of submerged-arc cladding process.

Submerged-arc cladding can be done using either alternating current (ac) or direct current (dc) power. Minimum dilutions are generally obtained with direct current straight polarity (electrode negative). However, many vessel fabricators use alternating current to eliminate arc-blow problems when cladding and welding thick sections of ferritic steels.

The molten weld pool is shielded from the atmosphere by a blanket of flux. Several publications discuss types, properties, chemistries, classifications, manufacturing techniques, and applications for various SA fluxes.^{37,39-43} This section will briefly review these areas.

Submerged-arc fluxes are classified by manufacturing technique as prefused, bonded, or agglomerated.³⁹ Prefused fluxes are produced by first melting the raw materials and then cooling the fused materials on chill plates or in water. The flux is then crushed and sized. Bonded fluxes are mixtures of raw materials bound together by sodium or potassium silicates. The mixture is cured at low temperatures and then sized. Agglomerated fluxes are similar to bonded fluxes except for the use of ceramic binders, which cure at relatively high temperatures [about 750°C (1400°F)], rather than sodium- or potassium-silicate binders. Raw materials for fluxes are primarily oxides of silicon, titanium, zirconium, aluminum, calcium, iron, manganese, and magnesium. However, other metal oxides, fluorspar, limestone, deoxidizers, and ferroalloys are commonly added. Ferroalloys and deoxidizers can be added only to bonded fluxes because temperatures required in production of prefused and agglomerated fluxes are too high.⁴⁴ Prefused fluxes can be collected and reused because they have good chemical homogeneity and are usually nonhygroscopic. Bonded and agglomerated fluxes tend to be more hygroscopic and may require rebaking before they can be reused. Also, removal of fines from these fluxes, especially for alloyed fluxes, may significantly alter the chemical contents of the deposits.

Slag/metal reactions for SA welding are similar in many ways to those encountered in steel making. Therefore, the chemical behavior of SA fluxes can be described fairly successfully on the basis of "basicity," as is sometimes done for slagged or fluxed steel-making processes. Using this chemical basis, fluxes can be divided into three groups: basic, amphoteric (neutral), and acidic.⁴⁵ They are often described by a basicity index (BI). One of the more popular formulas for predicting basicity is that proposed by Tulliani, Boniszewski, and Eaton:^{46,47}

$$BI = \frac{CaO + CaF_2 + MgO + K_2O + Na_2O + 1/2(MnO + FeO)}{SiO_2 + 1/2(Al_2O_3 + TiO_2 + ZrO_2)}$$

Values of BI less than about 1 indicate acid fluxes, and values over about 1.3 generally indicate basic fluxes.⁴⁸ Basic fluxes ordinarily produce lower silicon content deposits and less chromium loss than the

acid fluxes. However, the acid fluxes produce more easily detached slags and are capable of carrying higher currents and producing deeper penetrations.⁴⁹

Significant losses of oxidizable elements, such as chromium, niobium, and titanium, can occur during metal transfer with the SA process. These losses depend on the chemical composition of the flux and can be compensated for by ferroalloy additions (bonded fluxes only). Cladding fluxes that are considered "unalloyed" typically contain about 3% ferrochrome to compensate for chromium lost during metal transfer. Nuclear reactor fabricators rarely use fluxes with higher chrome enrichment for single-wire overlaying except for applications where high-silicon acid fluxes are required.⁴⁶

Another method of compensating for arc losses and for base-metal dilution is to use a higher-alloy filler wire. This method is often preferred because care must be taken in recycling highly alloyed fluxes. In addition, transfer of elements is more efficient from the wire than from the flux.⁴⁶

For each application, wire and flux must be matched to produce a deposit of the desired composition. Many manufacturers of welding consumables qualify and supply combinations of welding wire and flux to their customers for specific applications. However, for a given wire and flux combination, significant variations in deposit composition can result from changes in process variables. The controlling variables for single-wire overlaying are current type and polarity, arc voltage and current, travel speed, wire diameter, electrode stick-out, torch movement, torch position, and flux depth.⁵⁰ These variables must be controlled to produce a deposit of a desired composition.

Several modifications have been made to the single-wire SA process to increase its efficiency in cladding. The simplest modification, oscillation of the welding torch transverse to the welding direction, increases bead widths and deposition rates. Multiple electrodes also increase deposition rates. As many as six parallel electrodes have been successfully used to produce clad components. Also, deposition rates have been increased by metering an alloyed powder into the molten weld pool. Currently, the modification of the SA process with the most rapidly increasing popularity is the strip-cladding process. The following sections briefly discuss these modifications.

Oscillated submerged-arc cladding. Oscillation is usually used when single-wire SA cladding is performed and may also be used with multiple wire and strip cladding. Oscillation improves control of dilution, bead tie-ins, and uniformity of the clad. A disadvantage is the increased number of parameters to control, including oscillation width, oscillation frequency, and dwell time. These parameters, in addition to those previously mentioned, must be controlled to obtain desired bead shapes and contours, deposition rates, base-metal dilutions, and deposit chemistries.

Several types of oscillators using solid state electronic controls are currently available that allow excellent control of the oscillation parameters. However, many manufacturers feel that sufficient control for SA cladding can be obtained using less expensive pendulum-type, cam-driven oscillators. For a cam-driven oscillator, the width is adjusted mechanically, the frequency is determined by the cam speed and width adjustment, and the dwell time is determined by the cam configuration.

Three basic oscillation techniques are used in cladding: pendulum, straight line, and straight-line constant velocity.⁴⁸ The first two are similar, characterized by a slight hesitation (dwell) at both sides of the bead. However, the straight-line technique allows for more constant arc voltages and for control of dwell time. The straight-line constant-velocity technique produces the lowest dilutions because it has no dwell.

Multiple-wire submerged-arc cladding. There are three basic multiple-wire processes: multiple parallel-wired electrodes, multiple series-wired electrodes, and hot-wire addition. Two or more electrodes wired in parallel yield higher deposition rates than the single-wire process. Control of this process is very similar to that of the single-wire process in that all wires are fed by the same motor. As many as six wires have been fed simultaneously (Fig. 6), thus producing very high deposition rates. For the six-wire process the first electrode, which ties into the previous bead, is generally wired in reverse polarity (electrode positive), thus increasing the arc penetration at the tie-in and decreasing the probability of slag entrapment or lack of fusion between beads.⁴⁹ The remaining electrodes are wired in straight polarity (electrode negative) to decrease the overall dilution from the base metal. Also, the sixth electrode is generally staggered behind the plane of the other five electrodes to produce a tapered bead edge, which aids in the tie-in of the next bead. Adding oscillation can further increase bead widths and deposition rates. The primary disadvantage of this process is the complexity of the required equipment. For example, if one wire fails to feed, the whole process must be stopped. Care must be taken to ensure that wires are clean and free from kinks, burrs, or splices. Because of its complexity, the advantages of this process do not often justify its use.

Series-arc SA welding is often used for cladding purposes. With this process (Fig. 7) two welding electrodes are wired in series, normally to an ac power supply. Because there is no electric connection to the base plate, the electrode-to-work distance is very critical, with typical distances of $5 \text{ mm} \pm 1 \text{ mm}$ ($0.2 \text{ in.} \pm 0.04 \text{ in.}$).⁵¹ If the electrode-to-work distance is too small, high base-metal dilutions are encountered. If the distance is too large, the bead does not bond properly to the base metal. The addition of a third "cold" wire or metallic powder is often used to control the clad composition. Advantages include much higher deposition rates and lower base-metal dilutions than those for single-wire overlays. Primary disadvantages are the complexity of equipment and the necessity for close control of electrode-to-work distances.

Fig. 6. Schematic of six-wire submerged-arc cladding process.

Hot-wire SA cladding is a relatively new process⁵² (Fig. 8). It adds a "hot wire" that is resistance heated by a separate ac power source. When operating correctly, the hot wire is heated to its melting point as it is fed into the molten weld pool. With the SA process the hot wire is fed into the front of the weld pool, because feeding from the back interferes with the welding slag. Setup of this system is simpler than that of the gas-shielded hot-wire processes, because effects of arc radiation on the hot wire are not significant. Advantages of the process include high deposition rates at relatively low heat inputs and low base-metal dilutions. Disadvantages include complex equipment and difficult setups.

Submerged-arc cladding with powder additions. A relatively new modification of the SA welding process, which has gained some use in overlaying components with corrosion- and wear-resistant materials, is the addition of metal powders. A metal powder is accurately metered onto the base plate directly in front of the molten weld pool (Fig. 9). The alloy powder is melted by the welding arc, and the deposited weld metal is a combination of the wire, powder, and base metal. Advantages of the method include higher deposition rates with lower heat inputs. Lower dilutions can also be obtained, because much of the arc's energy is used to melt the powder rather than the base metal. Disadvantages include complexity of equipment and complexity of materials selection (i.e., a wire, powder, and flux combination must be chosen for this system) and

Fig. 7. Schematic of series-arc submerged-arc cladding process.

Fig. 8. Schematic of submerged-arc hot-wire cladding process.

Fig. 9. Schematic of submerged-arc cladding with metal powder additions.

use. This method has been successfully used with single-wire cladding and is being considered for use with strip cladding.

Submerged-arc strip cladding. The modification of the SA process increasing fastest in use is strip cladding. By far, the greatest amount of available literature concerning cladding deals with this process.^{37,53-64} The earliest reference to strip cladding was in 1963.⁵⁸ Even then it was considered an economical and viable cladding process.

Strip cladding is similar to single-wire SA cladding, except that a strip is substituted for the wire (Fig. 10). Electrical contact is made to the strip via a water-cooled busbar. Flux is often added both in front of and behind the welding arc. The critical welding parameters are the same as those previously mentioned for single-wire cladding. In some instances oscillation is also used. Dual strips are sometimes employed, meaning that a "cold" strip is laid onto the base plate in front of the molten weld pool. "Hot-strips" and metal powders have been used with the system, but neither has gained significant commercial acceptance.

Strips having dimensions ranging from 0.5 mm × 51 mm to 0.8 mm × 102 mm (0.02 in. × 2 in. to 0.03 in. × 4 in.) are available, with most common strip dimensions of 0.5 mm × 60 mm (0.02 in. × 2.4 in.).³⁷ Strips in widths from 102 to 180 mm (4 to 7 in.) have been tried but are considered impractical for most uses.⁵⁴ For wider strips, magnetic devices are

Fig. 10. Schematic of submerged-arc strip cladding.

often attached to the welding head to obtain acceptable surfaces, edges, and bead configurations (concavity).⁶¹ These devices also eliminate problems with magnetic arc blow.

The composition of a clad deposit depends on the critical welding parameters and on the strip and flux combination. The choice of a flux is much more critical for strip cladding than for single-wire cladding.⁶¹ This results from the larger size of the molten weld pools and the stringent surface requirements. The flux has significant effects on the deposit composition, dilution, arc characteristic, welding polarity required, bead shape, and surface appearance. There are several good discussions on the choice of fluxes for strip cladding.^{37,53-64} Welding current and travel speed are the most critical welding parameters for controlling deposit composition, although voltage and the orientation of the welding head with respect to the base plate also have some effect. The choice of welding polarity is largely dependent upon the flux.

Unlike the arc from a round electrode, a number of arcs from a strip electrode have been shown to dance back and forth across the surfaces of the strip and corresponding base plate.⁶⁴ These arcs move randomly along the surfaces and are transferred at the points of least resistance, generally at tips on the strip edges where previous drops have melted off. The arc dwells at these points for time intervals of up to 0.08 s.⁶¹ Metal transfer is primarily in the form of droplets with some short circuiting.

Advantages of the strip-cladding process include very high deposition rates, low base-metal dilutions, good surface quality and bead

configuration, and relatively low flux consumption. One disadvantage is the necessity to weld in the downhand (IG) position because of the large sizes of the molten weld pools (also exists for single-wire SA cladding). Also, the equipment is somewhat more complex than conventional single-wire equipment.

Gas metal-arc cladding. The gas metal-arc (GMA) process is defined as "an arc welding process wherein coalescence is produced by heating with an arc between a continuous filler metal (consumable) electrode and the work. Shielding is obtained entirely from an externally supplied gas, or gas mixture."³⁸ A schematic of the process is shown in Fig. 11. Cladding can be done either automatically or semiautomatically. The GMA process has some advantages over the previously described SA process for field fabrication. Because the molten weld pool can be smaller, out-of-position (vertical and overhead) cladding can be done. Also, the problems of building dams to retain the SA flux do not exist. One disadvantage is the intense heat and light emitted from the arc, which must be shielded from the welding operator and other workers in the area. Also, gusts of wind can blow away the arc shielding gas, thus causing defects in the welds. Relatively low deposition rates and high dilutions have limited its use for cladding except for special applications.⁶⁵

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Fig. 11. Schematic of gas metal-arc surfacing process.

The controlling variables for single-wire GMA cladding are arc current, voltage, electrode stick-out, travel speed, shielding gas, and electrode diameter. Oscillation is frequently used with the process for cladding. Constant-voltage power sources are most often used with adjustable, constant-speed electrode feeders, with the electrode feed rate directly dependent upon the current. Metal transfer can be by drop, spray, or axial-spray mode depending upon wire size, shielding gas, and current.^{66,67}

For cladding with the single-wire process, dilutions are generally lower with slower torch travel speeds because the arc is directed toward the molten cladding metal, rather than toward the base metal. For a given travel speed, dilution is a function of current and electrode stick-out only.⁶⁸ Dilution generally decreases as electrode extension increases and current decreases. Voltage does not significantly affect dilution.

Modifications of the GMA single-wire process are often used for cladding, the most common one being oscillated single-wire cladding. Two-wire GMA welding has been performed with the wires connected both in parallel⁶⁹ and in series.⁷⁰ Both two-wire processes, with the aid of oscillation, produce higher deposition rates, lower dilutions, and more uniform penetrations than does single-wire GMA. However, the two-wire GMA processes have not gained wide commercial acceptance for cladding.

Flux cored-arc cladding. The flux cored-arc (FCA) welding process has found limited use for cladding applications. The process is defined as "an arc welding process wherein coalescence is produced by heating with an arc, between a continuous filler metal (consumable) electrode and the work. Shielding is obtained from a flux contained within the electrode. Additional shielding may or may not be obtained from an externally supplied gas or gas mixture."³⁸ The process is basically the same as the GMA process, except that shielding is provided by a flux rather than by a gas. The critical parameters for the FCA process are identical to those previously described for the GMA process. The flux is contained entirely within the hollow wire electrode. In general, the electrode is produced by rolling a thin strip of material into a U-shaped cross section. Flux is then added and the strip (with flux inside) is further rolled into a circular cross section with the flux-cored wire then swaged or drawn to the desired diameter. The flux characteristics are similar to those described earlier for the SA process. Alloying elements can also be added to the core. For example, stainless steel wires are often made by using carbon steel strips and adding chromium and nickel to the core material.

The only reported modification of this process is the six-wire cladding process.⁷¹ With this process, six electrodes are wired in parallel, in a manner similar to the six-wire SA process previously described. High deposition rates and good control of dilution can be obtained. The primary disadvantages include intense heat and light emitted from the arc and very complex equipment. This process has gained only limited use for cladding in this country.

Shielded metal-arc cladding. The shielded metal-arc (SMA) welding process has found wide use for cladding applications. It is defined as "an arc welding process wherein coalescence is produced by heating with an arc between a covered metal electrode and the work. Shielding is obtained from decomposition of the electrode covering. Pressure is not used and filler metal is obtained from the electrode."³⁸ Other common names for the process are manual metal-arc (MMA) and "stick" welding. Because the electrode is usually manipulated manually and the process produces a relatively small molten weld pool, cladding can be done in other positions besides the downhand (IG) position. Also, SMA is used effectively to repair defects in clads produced by other processes. This process is, therefore, well adapted to field fabrication.

The SMA electrode is a coated metal wire (core wire). A schematic of the process is shown in Fig. 12. The coating consists of flux, alloying elements, a binder, and other elements. Considerations for formulation of the electrode coating are similar to those described previously for SA fluxes. The coating is formulated to (1) facilitate electrode extrusion, (2) stabilize arc characteristics, (3) produce a deposit of desired composition, (4) protect the molten weld pool from the atmosphere, and (5) produce a slag that is tough and adherent during solidification but easily removed when cool. Electrodes are produced by first mixing dry ingredients, to which mixture a binder is added (usually sodium or potassium silicate). The wet mixture is then extruded around a core wire (straight and cut-to-length), and the moisture baked from the electrodes. Alloying can be done through the coating, and stainless steel electrodes are often produced from carbon steel core wires with nickel and chromium added to the coating.

Fig. 12. Schematic of shielded metal-arc surfacing process.

The primary variable for the SMA process is the operator technique.⁷² Because the process is so dependent upon operator technique, dilutions vary over a wide range and are generally higher than those for the automated processes. Two- or three-layer techniques are most often used for cladding carbon steel components with stainless steels. Overlapping bead techniques are also used to minimize dilutions.

The SMA process is probably the most widely used cladding process because of its versatility and because the equipment required for the process is simple and inexpensive. Deposition rates are, however, relatively low, and highly skilled labor is required. Therefore, SMA cladding is generally used only for those cases in which the higher-deposition-rate automated processes cannot be used, as for cladding tight corners and insides of nozzles, for back-cladding over weld seams in clad plate, and for repair of existing clads.

3.3.3.2 Nonconsumable-electrode overlaying. For the nonconsumable-electrode overlaying processes, coalescence is produced by heating with a source (arc or flame) while filler wire is fed into the weld pool independently of the heat source. Molten weld pools are protected from the atmosphere by shielding gases or by refractory slags. Detailed discussions of these processes are given in the following sections.

Gas tungsten-arc cladding. The gas tungsten-arc (GTA) welding process is used for several cladding applications. The GTA process (Fig. 13) is defined as "an arc welding process wherein coalescence is produced by heating with an arc between a single tungsten (nonconsumable) electrode and the work. Shielding is obtained from a gas or gas mixture. Pressure may or may not be used and filler metal may or may not be used. (This process has sometimes been called TIG welding.)"³⁸ The filler metal is fed into the molten weld pool independently of the tungsten electrode and can be fed either cold or hot. Cold wire is fed into the leading end of the weld pool so that it can be melted by the heat of the arc. Because the wire is nearly molten when it enters the pool, hot wire additions are generally made to the trailing end of the weld pool.

A constant-current dc power supply is used for the welding arc, and the electrode is usually connected to the negative lead (straight polarity). When a hot wire is employed, a separate ac power source is used for resistance heating of the wire. The process requires careful control of the welding conditions, particularly the arc voltage (arc length), and, as a result, manual GTA cladding requires highly skilled labor. For automated GTA cladding, constant arc lengths (voltages) must be maintained by mechanical devices or by electronic automatic voltage control (AVC) heads.

Cold-wire GTA is used for cladding small components (such as nozzles and small pipes) or in tight spaces where other cladding processes cannot be used. It is also used to repair defects in existing clad metals. Hot-wire GTA is capable of higher deposition rates (approaching that of single-wire SA) and better control of dilution than the cold-wire process.

Fig. 13. Schematic of gas tungsten-arc surfacing process.

It has gained limited use for production cladding of critical components, such as cladding of forged low-alloy steel tube sheets with high-nickel alloys. Because the molten weld pool for the hot-wire process is much larger than that for the cold wire process, special care must be taken to maintain adequate shielding from the atmosphere. In general, the GTA process has not been used extensively for production cladding applications.

Plasma-arc cladding. The plasma-arc (PA) welding process is becoming popular for production cladding applications. It is defined as "an arc welding process wherein coalescence is produced by heating with a constricted arc between an electrode and the workpiece (transferred arc) or of the electrode and the constricting nozzle (non-transferred arc). Shielding is obtained from the hot, ionized gas issuing from the orifice which may be supplemented by an auxiliary source of shielding gas. Shielding gas may be an inert gas or a mixture of gases. Pressure may or may not be used, and filler metal may or may not be supplied."³⁸ The PA process is similar to the GTA process except that the arc is constricted by a copper orifice nozzle within the torch. Because of the constriction of the arc, control of arc voltage is not as critical as for the GTA process. Therefore, training of manual PA operators is not as difficult as training of manual GTA operators. To initiate the welding arc, a pilot (low current) arc is often ignited between the electrode and the constricting nozzle. The ionized gas from the pilot arc aids in igniting the transferred arc between the electrode and the work.

For overlaying, two primary methods of feeding consumables are used: powder and hot-wire additions. For the powder feed method (Fig. 14), powder of the desired composition is fluidized and carried into the arc by an inert gas. The powder is fed into the welding torch in the area around the constricting nozzle, where it is then melted as it passes through the plasma and into the weld pool. This method is used for cladding smaller components with hard-facing alloys but has not been used significantly for stainless steel cladding of larger ones.⁷³ The hot-wire method is called hot-wire plasma-arc cladding or, sometimes, gas-metal-plasma-arc cladding. Because the use of a single hot wire often leads to arc instability in this process, two hot wires are commonly used with an ac current between them⁷⁴ (Fig. 15). The powder feed and hot-wire PA processes, with the aid of oscillation, produce high deposition rates, with excellent control of dilution and deposit thickness. Dilutions can be reliably maintained in the 5 to 10% range.

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Fig. 14. Schematic of plasma-arc powder surfacing process.

Fig. 15. Schematic of hot-wire plasma-arc surfacing process.

The hot-wire plasma-arc cladding process is gaining popularity both in the United States and abroad.⁷⁵⁻⁷⁹ This process has been shown to be a high quality and economical method of producing clad materials. Applications have included cladding of tube sheets and pressure vessels for chemical, nuclear, and petrochemical uses. The primary disadvantages of the process are the complexity of the equipment and the large number of welding variables to control.

4. WELDABILITY OF MATERIALS

Several materials are of interest for coal conversion applications. Base metals under consideration are ferritic steels typically used for nuclear and petrochemical pressure-vessel fabrication. These include plain carbon steels (e.g., SA-516 grade 70) and high-strength, low-alloy steels (e.g., SA-533 grade B class 1, SA-387 grade 22 class 2, and SA-508 class 2). Other high-strength steels, such as SA-543 and SA-508 classes 4 and 5, are sometimes used through an ASME code case but are not currently code approved.⁸⁰ Ferritic steel pipe and forging materials of similar compositions are also of interest and should be given the same considerations as the above pressure-vessel materials. Possible cladding materials include stainless steels and selected higher-nickel alloys. Only weld overlays will be considered specifically in this section, because the greatest weldability problems exist with this lining technique. Similar considerations exist for other types of lining where welding is involved (e.g., applied linings).

4.1 Base Metals

The primary ferritic steel base-metal problems encountered with weld overlaying are hydrogen cold cracking, reheat cracking, and hot cracking. These cracks occur in the weld heat-affected zone (HAZ) immediately under the clad metal. Hydrogen cold cracks usually occur at temperatures below 93°C (200°F) and are usually transgranular.⁸¹ Reheat cracks generally occur upon reheating a clad component to postweld heat treatment (PWHT) temperatures and are intergranular in nature. Hot cracks occur intergranularly during welding when the HAZ is heated to just below the bulk melting point of the base steel.

Hydrogen cold cracking, which can occur hours or days after cladding, is sometimes referred to as delayed cracking.⁸¹ Three conditions must exist for this cracking to occur: dissolved hydrogen in the HAZ, tensile stresses, and low ductility microstructures. Hydrogen can be introduced to the microstructure from several sources. Dirt, grease, or moisture on the surfaces to be clad and on the cladding consumables is one major source. Also, hydrogen can be introduced through the shield gas or welding fluxes. In the welding arc, atomic hydrogen forms, dissolves readily in the weld metal and, upon cooling, diffuses into the base metal. When cooling is very rapid (as it is for many welding processes), the material in the HAZ that was austenitized during welding can transform to martensite. Because hydrogen has a very low solubility in martensite, it tends to collect at structural discontinuities. At this point the atomic hydrogen unites to form hydrogen gas, which exerts internal stresses on the discontinuities. High residual stresses can also exist as a result of restraint during cladding. Both of these stresses tend to open the discontinuities and form crack tips. Untempered martensite in the HAZ has low ductility, and, if stresses are high enough, the cracks can propagate readily from discontinuity to discontinuity.

The tendency for a base metal to form cold cracks is related to its hardenability (or ease of forming martensite upon cooling from austenitizing temperatures). Hardenability is strongly dependent on carbon content; other elements increase hardenability to a much lesser degree. The effects of composition have, therefore, been described in terms of a "carbon equivalent."⁸¹ A formula commonly used for calculating carbon equivalent (CE) is

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Ni}{20} + \frac{\%Cr + \%Mo}{10} + \frac{\%Cu}{40} .$$

In general, as the CE increases, the hardenability and the susceptibility to cold cracking increases.

Several methods are available to reduce cold cracking. Base materials with low cracking susceptibility should be chosen whenever possible. Surfaces to be clad and cladding metals should be cleaned

thoroughly before welding begins, and weld overlaying should not be done in the snow or rain. For SMA overlaying, low-hydrogen electrodes should be used and should not be exposed to the atmosphere for extended periods unless they are stored at temperatures high enough to avoid moisture pickup [usually about 85°C (185°F) for stainless steels]. Likewise, SA fluxes that tend to be hygroscopic (bonded and agglomerated) should not be open until immediately before use or should be stored in an oven. Fluxes and electrodes that have been exposed to the atmosphere at room temperature for more than 24 hr should be reconditioned and rebaked before use. Care should be taken with the gas-shielded processes to avoid the collection of moisture in the shielding-gas bottles that can occur if bottles are not maintained correctly. Finally, preheat treatments and PWHTs should be performed. The preheat treatment drives moisture from the base-metal surface, retards the cooling rate in the HAZ (yielding tougher microstructures), and lowers residual stress buildup. The PWHT relieves residual stresses that build up during cladding and sometimes imparts extra toughness to the HAZ. The ASME Boiler and Pressure Vessel Code gives suggested preheat (Sect. VIII, Div. II, Appendix 14) and mandatory PWHT (Sect. VIII, Div. II, Table AF 402.1) techniques. Proper use of these techniques will greatly reduce the likelihood of hydrogen cold cracking.

Reheat cracks occur in the HAZ upon heating to PWHT temperatures and are most often referred to as underclad cracks. These cracks were first observed in Europe in 1970 and have been the subject of many investigations since then. This topic has been reviewed extensively in the literature and, therefore, will not be considered in great detail in this review.⁸²⁻⁸⁶ However, reheat cracks do present very serious problems because they are inherent to the pressure vessel steels commonly used for nuclear and petrochemical applications. This cracking is more serious for certain grades of steel. For instance, SA-508 class 2 is significantly more susceptible to reheat cracking than SA-533 grade B class 1. Also cracking is more serious for the higher-heat-input cladding processes, which are more desirable from an economic standpoint.

Reheat cracks are intergranular and have been reported in lengths of up to 10 mm.⁸⁴ Depths of cracks, measured from the fusion line, range up to 4 mm. These cracks are always observed beneath the overlap area of two adjacent weld beads in the HAZ that has been affected by the heat from both beads. Cracking is believed to occur upon heating during PWHT, at temperatures around 600°C.

Three major factors affect reheat cracking: composition, microstructure, and residual stresses. A generally accepted formula for calculating susceptibility to this cracking was derived by Nakamura in Japan:⁸⁷

$$\Delta G = \%Cr + 3.3(\%Mo) + 8.1(\%V) - 2 .$$

Steels are considered to be crack sensitive with value of $\Delta G \geq 0$. However, this formula only applies to steels in the composition range studied by Nakamura (boron-containing steels with less than 1.5% chromium and less than 0.18% carbon).

Several methods are available for minimizing reheat cracking. The first is to avoid susceptible steels and high-heat-input overlaying processes whenever possible. When these steels and processes are used, the Europeans usually use two-layer cladding techniques to temper the susceptible HAZs. However, two-layer cladding is not economical and U.S. manufacturers generally prefer single-layer clads. The U.S. Nuclear Regulatory Commission (NRC) will allow the use of high-heat-input cladding processes (10-cm strip cladding or six-wire cladding) with susceptible base metals, if the manufacturer can prove that he does not have a reheat cracking problem. Because these cracks are too small to be found by conventional radiographic or ultrasonic testing, detection is usually accomplished by grinding away an area of the clad (window grinding) and magnetic-particle testing. More recently, ultrasonic techniques have been developed that can find these minute cracks. There are other methods that have been suggested for reducing cracking, including renormalizing the clad HAZ by surface induction heating, using a staggered cladding sequence, not using machined surfaces, using two-step PWHT (with a lower temperature soak period), and using cladding metals with expansion coefficients close to those of the base steels.⁸⁸ All of these methods have not yet been proven.

Reheat cracks have been a major topic of concern for heavy section fabricators since they were first discovered. Methods for finding and eliminating them have been developed; some of the methods are, though, uneconomical and undesirable for the fabricator. Therefore, the actual effects of these cracks on properties are an important consideration. From most of the fracture toughness work done in the past, the general consensus is that these cracks do not affect the toughness properties of the steel.⁸⁵ However, more work needs to be done in this area.

The third type of cracking is hot cracking, which results from liquation of low-melting-point constituents in the grain-boundary areas of the HAZ. Hot cracking is also called underclad cracking by some investigators and is sometimes confused with reheat cracking. Residual tensile stresses, along with weakening of the grain boundary by liquation, lead to intergranular separations (hot cracking) in the HAZ during solidification of the clad. The low-melting constituents are generally recognized to be compounds of sulfur (ferrous sulfide, for example).⁸² This problem can be controlled by making additions of manganese to the ferritic steel base metal, in amounts such that the manganese to sulfur ratio is greater than 60. The higher-melting manganous sulfide forms more readily than ferrous sulfide, and hot cracking is minimized. Another method is to use lower-heat-input welding processes that yield smaller grains in the HAZ and a smaller HAZ, and thus lower the susceptibility to hot cracks.

4.2 Cladding Metals

Cladding materials of interest for these applications are austenitic stainless steels (such as types 308, 309, 310, 316, 320, and 347) and higher nickel austenitics (such as Inconel 82 and nickel 61). Several factors can contribute to weakening the integrity of weld overlays of these materials. First, discontinuities in the clad can occur during or after overlaying in the form of inclusions, lack of fusion, porosity, fissuring (during solidification and reheating), and cracking due to brittle structures. These discontinuities can propagate under certain conditions, but there are varied opinions of their effects on properties. In addition, metallurgical changes (sensitization, sigma phase formation, and carbon diffusion) to the cladding microstructure during fabrication and service can, under certain conditions, lead to degradation of mechanical properties and corrosion resistance.

The chemical composition of a weld overlay depends on composition of cladding metal (determined from undiluted weld metal), composition of base metal, and dilution; and can be calculated knowing these variables. The structures of the higher nickel materials are almost always fully austenitic (face-centered cubic structure).⁸⁹ The chromium-nickel austenitic stainless steels, though, often contain more than one phase in the as-deposited structure. These materials are primarily austenitic with varying amounts of ferrite, martensite, and sigma phases determined by the composition and cladding conditions.⁸⁸

The amounts of ferrite and martensite present in the austenitic structures can be estimated from a constitutional diagram similar to the one shown in Fig. 16 (taken from the ASME code).⁹⁰ Chromium (ferrite formers) and nickel (austenite formers) equivalents are calculated from the following equations:

$$\text{Chromium equivalent} = \%Cr + \%Mo + 1.5(\%Si) + 0.5(\%Nb) ,$$

$$\text{Nickel equivalent} = \%Ni + 30(\%C) + 0.5(\%Mn) + 30(\%N) .$$

These values are then plotted and the percentages of phases present are read directly from the diagram. Care should be taken in using this technique, however, because the as-clad microstructure is also dependent on cooling rate. Cooling rates can vary significantly, depending on cladding conditions. Another method of quickly determining the phases present is by using magnetic measuring devices, such as a Magne-gage, Ferrite Scope, Severne gage, etc. Austenite is nonmagnetic, whereas ferrite and martensite are ferromagnetic. When properly calibrated, these instruments can quickly give an indication of percentage of magnetic phase present. The most expensive method of determining the structure is by using metallographic techniques, such as quantitative television microscope (QTM) evaluation.

Fig. 16. Constitution diagram for stainless steel weld metals. Note that the actual nitrogen content is preferred. If this is not available, the following applicable nitrogen value shall be used: GMAW welds — 0.08% (except self-shielding flux cored electrode GMAW welds — 0.12%); welds of other processes — 0.06%. Source: American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code. An American National Standard*, ANSI/ASME BPV-III-I-NB, New York, 1977, Fig. NB-2433.1-1.

Sigma phase is not common in as-clad structures but can occur where high-heat-input processes are used. It forms most readily from ferrite phase but can also form from austenite in high chromium areas.⁹¹ The transformation to sigma phase is time and temperature dependent and occurs in the temperature range 500 to 900°C (930 to 1650°F) with longer times at these temperatures producing larger amounts of sigma phase. The percentage of sigma phase can be determined by only metallographic techniques.

Fully austenitic overlays are generally susceptible to fissuring (hot cracking), which can occur upon solidification or reheating by a subsequent overlay pass (microfissures). Solidification cracks are generally very large and can be found by visual or dye-penetrant examination. However, microfissures are often subsurface and difficult to find by conventional nondestructive examination (NDE) techniques. For

the austenitic stainless steels, the tendency for fissuring is greatly reduced by the presence of a small amount of delta ferrite in the structure. The amount of ferrite required to eliminate fissuring varies from material to material but is generally recognized to be in the range of 5 to 10%. Lundin and Spond⁹² ranked several austenitic stainless steels in ascending order of amount of ferrite required to avoid fissuring: types 16-8-2, 316L, 308, 309, 318, and 347. The compositions of these materials should be adjusted to produce a small amount of delta ferrite in the as-clad structure.

The higher-nickel austenitic materials are also very susceptible to fissuring, which can be controlled in many cases by using high-purity welding consumables and by cleaning surfaces thoroughly before cladding. The most important precaution is to limit the concentration of low-melting-point constituents in the overlay. Titanium is often added to stabilize the overlay and to produce finer grain sizes (reducing the fissuring tendency). Also, manganese is often added to tie up sulfur in the structure and to decrease fissuring. Nickel-copper austenitics, such as type 320 stainless steel, have a very low solubility for iron, with concentrations higher than the solubility limit, causing precipitates in grain boundaries and fissuring.⁹³ This makes weld overlaying of carbon steels with these materials very difficult and requires that dilution from the base metal be held to the minimum. In some cases an intermediate layer of nickel (such as Inconel 82 or nickel 61) must be used to avoid cracking of the nickel-copper overlays. This intermediate layer has a higher solubility limit for iron and is compatible with the nickel-copper overlay. Another method of reducing fissuring is to use low-heat-input cladding processes, because these processes produce smaller structures, lower dilutions, and lower stresses.

Cracking of austenitic stainless steel can result from the presence of brittle structures, such as martensite (caused by high dilutions), sigma phase, and high carbon areas in the clad metal (caused by carbon diffusion from the base metal).⁹⁴ These cracks are generally large and occur during a stress cycle after welding (during testing or in service). Martensitic structures can be eliminated in many instances by using low dilution processes or intermediate nickel-clad layers. Both sigma-phase formation and carbon diffusion occur after welding during a PWHT or in-service cycle. Sigma-phase formation has been discussed previously in this section and can be minimized by reducing ferrite in the as-welded structure to the lowest level possible that does not produce fissures. Carbon diffusion into the austenitic stainless steel clad can be effectively controlled by the use of a nickel intermediate layer, because carbon has a much lower diffusion rate in austenite. This eliminates embrittled, carbon-rich bands in the clad metal and weakened, decarburized areas in the HAZ, which sometimes cause cracks.

Other discontinuities common to all weld deposits are lack of fusion, inclusions, and porosity. Lack of fusion is an area where the clad metal is not integrally bonded to the base metal and often results from attempts to produce low-dilution overlays. These areas can lead to

cladding and base metal separations during fabrication (stress relieving) or in service.⁹⁴ Inclusions are foreign materials (such as tungsten or oxides) that are trapped in the weld metal during solidification and can result from improper cladding or cleaning techniques. Inadequate weld-bead overlaps or poor bead contours can also lead to trapped inclusions. Lack of fusion and inclusions can be reduced by proper cladding procedure development and control. Finally, porosity is caused by excess dissolved hydrogen or nitrogen gas in the weld pool. Porosity caused by hydrogen gas can be controlled by methods described previously to control hydrogen cold cracking. Maintaining correct arc lengths and adequate shielding can prevent excessive additions of nitrogen gas to the molten weld pool.

The effects of these discontinuities on properties have been the topic of several investigations. It is generally accepted that large-scale discontinuities in the clad are undesirable and should be repaired if found during fabrication.⁹⁵ However, with the advent of in-service inspection requirements (Sect. XI, ASME Boiler and Pressure Vessel Code) for large pressure vessels and components, those discontinuities not found during fabrication may be found during service. Judgments will have to be made on a case-by-case basis to determine if the discontinuities impair the integrity of the component. Repair of components during service is very expensive and time consuming. For example, in the early 1960s, cracks were found in the stainless steel cladding of four water-reactor pressure vessels during service.⁹⁶ These cracks had propagated through the clad by low cycle fatigue but had not propagated into the base metal. After a thorough investigation, it was decided that the cracks would not propagate further and that the components should be allowed to operate without repair but under close surveillance. Much care should be taken to avoid cladding materials and processes that have a high probability of incurring these types of in-service problems.

Although large-scale discontinuities are well understood and are easily found by NDE, the effects of microscopic discontinuities (such as microfissures) are not as well understood. Because these discontinuities are not found as easily by conventional NDE techniques, there is concern that they may propagate during fabrication or in service. It is the general consensus of investigators that the tensile, toughness and fatigue properties of austenitic stainless steel clads will not be significantly affected by these micro-discontinuities.^{91,96,97} However, brittle structures in the clad, especially martensite, should be avoided whenever possible.

Finally, stainless steel cladding materials are susceptible to sensitization (precipitation of chromium carbides in grain boundaries that leaves chromium-depleted adjacent areas). Sensitization can occur when unstabilized stainless steels are heated in the range of 430 to 820°C (800 to 1500°F) either during stress relief or in service. Under certain conditions, especially where halide ions are present, sensitized materials are very susceptible to intergranular corrosion and to stress-corrosion cracking. The best way to inhibit these problems is to use

stabilized (such as type 347) or low carbon (such as type 309L, 308L, etc.) grades of austenitic stainless steels that are not as readily sensitized. Also, finer microstructures produced by the lower-heat-input processes improve corrosion resistance for all grades.⁹⁸ For water-cooled-reactor applications, "intergranular corrosion of sensitized steel does not occur in reactor coolant water, with or without oxygen, with pH variations between 7 and 11 and at temperatures up to about 340°C (640°F)."⁹⁹ Therefore, with carefully controlled coolants, many reactor fabricators do not worry about in-service corrosion of sensitized clads. Care must be taken, though, during fabrication to clean all clad surfaces (dirt or welding slag can result in crevice corrosion attack) and to limit exposure of unclean surfaces to moisture. If possible, materials and processes that control sensitization should be used. If not, care should be taken both during fabrication and in service to keep sensitized materials away from environments that cause corrosion.

5. SUMMARY

Several methods are available to produce ferritic steel components lined with corrosion-resistant layers. For low-temperature-low-thermal cycling applications, applied linings may be a good choice. However, for more critical applications, integral cladding is generally preferred. Integral cladding may be performed by a variety of methods, including solid state cladding, braze-bond cladding, and weld overlay (fusion) cladding. The choice of lining process should be made after careful consideration of base metals, cladding metals, and the service requirements for the lined component.

With all of these processes, welding of some sort or heating to high temperatures is required to apply the lining. Lined components often go through several stress-relieving treatments before fabrication is completed. In service, many lined components are subjected to relatively high temperatures and stresses. Because the coefficients of thermal expansion of the base metals are significantly different from those of many of the possible cladding metals, these thermal cycles can build up large stresses that may have serious effects on the integrity of the clad.

Large-scale discontinuities, resulting from fabrication or service, are sometimes present in the cladding metals or the associated base-metal HAZs. Under certain conditions the thermal stresses, combined with applied stresses, may be large enough to propagate these discontinuities. The presence of micro-discontinuities, however, such as microfissures in clads and reheat cracks in base-metal HAZs, is not generally considered to be detrimental to the properties of a clad component. Larger discontinuities are readily found by conventional NDE techniques and should be repaired if possible. However, if repair is impossible or very difficult (as may be the case for discontinuities found in service), a detailed evaluation of effects on the integrity of the component should be performed.

Several changes to the microstructure of cladding materials can occur as a result of heating during fabrication and service. These include formation of sigma phase, sensitization, and carbon diffusion. Brittle structures such as martensite can also form in the weld-overlayed cladding metals as a result of excessive dilutions. These structures can seriously degrade the integrity of a clad under circumstances in which stresses are high or corrosive environments exist. Measures should be taken to avoid their formation whenever possible.

The ability of a lined component to withstand the conditions for which it is designed should be the most important consideration when choosing materials and processes. Economics should be the second consideration. As a result, lining processes and materials that provide minimum required properties at the lowest cost are usually chosen and less expensive lining techniques are continually being developed, particularly for the weld overlaying processes. The trend in the United States has been toward single-layer overlays made with high-heat-input processes. As has been discussed in the text, high-heat-input processes and single-layer techniques can sometimes lead to problems in the cladding metal and base metal. Application of two or more layers is often desirable, particularly if the intermediate layer is a nickel-base alloy. However, multiple layer techniques are expensive (especially with high-nickel interlayers) and are generally used only for critical applications.

Finally, when designing a component that requires lining, consideration should be given to all of the above fabrication problems. Designers and engineers often choose materials merely on the basis of strength or corrosion resistance. Equal consideration should be given to the ease of fabrication with these materials.

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