

Literature Review

The comprehensive literature review sheds light on ongoing research goals for creating electrode coatings for use in dissimilar welding in power plant applications. It discusses the challenges associated with the design and development of electrode coatings. This chapter also addresses issues related to the fabrication of dissimilar welds and their performance at elevated temperatures. Furthermore, it identifies gaps in research and areas with potential for further investigation.

2.1 Need for power generation

The need for power generation is critical to support modern society's demands, ensuring reliable electricity for residential, commercial, and industrial activities. It is essential for economic growth, technological advancement, and improving quality of life. As energy consumption rises, sustainable and environmentally friendly power generation solutions are increasingly necessary to meet demand and mitigate environmental impacts. Coal is a prominent fuel source for power generation globally, with substantial reserves distributed worldwide, totaling 860.93 billion tonnes as of 2012. Approximately 41% of the world's power generation relies on coal due to its cost-effectiveness compared to oil and natural gas. However, its usage poses significant environmental challenges, primarily due to its high CO₂ emissions, which contribute to concerns like global warming. To address these issues, there is a growing focus on adopting advanced ultra-supercritical (A-USC) power plants, which offer enhanced efficiency and reduced emissions. Achieving this involves initiatives aimed at increasing steam temperature (>700°C) and pressure (27.6-34.5 MPa). However, realizing these goals necessitates the development of high-temperature materials with superior creep and corrosion resistance at elevated temperatures (A. H. V. Pavan et al., 2015b).

2.2 Advancements in coal for A-USC power plant

Coal represents the largest individual source of CO₂ emissions in the power sector, posing significant concerns regarding its role in climate change. India is interested in implementing clean coal-based power production technology to reduce CO₂ emissions, maximize energy efficiency, and decrease the amount of coal needed to generate one unit of electricity. Therefore, implementing such technology would improve the nation's energy security by extending the life of coal reserves. Clean coal advancements are now in various stages of development around the globe. Different nations are exploring innovative approaches like advanced ultra-supercritical, ultra-supercritical, supercritical, and integrated gasification combined cycle for power generation. Many countries worldwide are adopting higher steam parameters to enhance efficiency and consequently reduce CO₂ emissions. Supercritical technology has been commercially deployed on a global scale, including in India. Supercritical power plants operate with higher steam parameters, resulting in higher efficiency, reduced coal consumption, and minimized carbon dioxide emissions (S C Chetal et al., 2015).

2.3 Need of candidate materials for A-USC power plants

The need for candidate materials for advanced ultra-supercritical power plants is critical. These advanced power plants operate at higher steam temperatures and pressures, requiring materials with superior mechanical properties, creep resistance, and corrosion resistance. The development and selection of appropriate materials are essential to ensure the reliability, efficiency, and longevity of A-USC power plants. Identifying and testing

candidate materials that can withstand these extreme conditions will help achieve the desired improvements in performance and environmental impact, ultimately contributing to more sustainable and efficient power generation.

Advancements in technology, such as the adoption of supercritical and ultra-supercritical steam cycles, offer promising solutions for improving the overall performance of coal-fired power plants. These innovations can significantly contribute to enhancing the sustainability and competitiveness of coal-based electricity generation in the global energy landscape. Different materials will be used for the waterwall, reheater, boiler tubing, and superheater zones of the boiler, with each material optimized based on the steam parameters. In the development of AUSC technology, one of the most crucial factors is the selection of materials for high-temperature zones. Apart from their physical properties, the selection criteria for materials across various components of the AUSC plant should also include their adherence to the ASME Code (S. C. Chetal et al., 2015). The materials chosen for AUSC (advanced ultra-supercritical) plants operating at 720°C steam temperatures need to meet several criteria:

- (a) Higher mechanical strength,
- (b) Minimum coefficient of thermal expansion and higher thermal conductivity.
- (c) Good weldability and formability
- (d) Higher corrosion resistant
- (e) Adequate interaction between creep and fatigue
- (f) Industrial availability and confidence in indigenous development are important factors for practical implementation.
- (g) The materials should also offer economic benefits.

Some of the newer materials proposed for use in AUSC plants include:

- 1. T-23 steel is recommended for water wall applications.
- 2. T-91 steel is suggested for use in superheater and reheater tubing.
- 3. 304HCu austenitic stainless steel is proposed for the final stage of superheater tubing.
- 4. Nickel-base alloy 617 is recommended for use in the tubing of the last stage of the reheater and superheater, particularly in the hottest zone.

Various candidate materials are used in A-USC power plants. The material selection is based on their application in the power plant. Hence, some of the A-USC materials and their chemical compositions are detailed by past researchers (S. C. Chetal et al., 2015; Xie et al., 2015). In 1975, INCO Alloys International introduced Inconel 617, a superalloy primarily strengthened through a solid solution mechanism. It consists of a Ni-Cr-Co γ -matrix enriched with a high proportion of Mo (9%), along with minor additions of Al and Ti to enhance γ' precipitation strengthening (Lin et al., 2011). ThyssenKrupp VDM in Germany further refined Alloy 617 to create Alloy 617B, prioritizing enhanced resistance against creep. This variant meticulously controls the concentrations of Ti and Al and introduces boron to reinforce grain boundaries. Sometimes identified as 617CCA or 617Mod, Alloy 617B signifies an optimized version engineered to withstand creep deformation. Nimonic 263 originated from Rolls-Royce in 1971 as a high-strength, corrosion-resistant nickel-based superalloy. Its foundation lies in a Ni-Co-Cr austenitic matrix, augmented by a substantial Mo content (6%) for additional solid solution strengthening. Particularly notable are the additions of 0.6% Al and 2% Ti, which facilitate the formation of around 10% $\text{Ni}_3(\text{Al}, \text{Ti})$ type γ' precipitates, resulting in effective solid solution and precipitation strengthening. Furthermore, the inclusion of boron serves to strengthen grain boundaries, resulting in a synergistic improvement in high-temperature creep resistance. In 2000, Special Metal Corp. (SMC), based in Huntington, USA, introduced IN 740 superalloys. This alloy was developed for the European A-USC project, which demanded steam parameters of 35 MPa and 700°C. Under these conditions, the reheater and superheater are subjected to fire-side metal temperatures of 750-760°C. Notably, the stress rupture strength of 100 MPa over 105 hours and corrosion resistance (limited to ≤ 1 mm cross-section loss over the same duration) are crucial for these components. Inconel 740 stands out for possessing better stress rupture and superior resistance to corrosion among materials readily available in the market, making it capable of

meeting the stringent requirements mentioned above. Haynes International developed the Haynes 282 in 2005. It emerges as a nickel-based superalloy renowned for its corrosion resistance and exceptional creep strength. Initially conceived as a replacement for Waspaloy in various aerospace components, Haynes 282 was specifically engineered to be weldable, addressing a critical limitation of its predecessor. While Waspaloy is esteemed for its performance within the intermediate temperature range of aerospace applications, Haynes 282 falls within the subclass of γ' -strengthened superalloys. It features a composition comprising 20% Cr, 8.5% Mo, 57% Ni, and 10% Co for solid solution strengthening, alongside 1.5% Al and 2.1 % Ti to facilitate γ' precipitation strengthening.

Austenitic stainless steel stands as another prevalent steel variant extensively employed in power plants. The annual estimated consumption of austenitic stainless steels exceeds 20,000 tons (Mirshekari et al., 2014). Austenitic stainless steel finds widespread application across diverse sectors, including the aerospace industry, power plants, cryogenic engines, high-temperature corrosive environments, and structural components of nuclear reactors. This popularity is owed to its exceptional corrosion resistance, high ductility, excellent formability, and superb weldability, attributes facilitated by its low carbon content (Sabzi et al., 2019). Austenitic stainless steel typically comprises 17-20% chromium and minimal carbon content. Additional elements like Ni, Mo, N, Cu, and Mn are incorporated to form the austenitic structure. This type of steel, though costly, is favored for high-temperature applications due to its exceptional creep strength and resistance to oxidation. Within the 300 series, austenitic stainless steels are preferred for thermal power plant components, renowned for their superior corrosion resistance and mechanical properties at elevated temperatures. Meanwhile, the 200 series contains lower nickel content compared to the 300 series, making it suitable for applications requiring moderate corrosion resistance at a more economical cost. Among the frequently employed advanced stainless steel grades are 347HFG, super 304H, and 310HCbN for A-USC applications (Siefert and David, 2014).

2.4 Need of welding for A-USC power plants

Welding plays a crucial role in power plants for several reasons:

1. **Construction and Maintenance:** Power plants involve the assembly of large structures, piping systems, boilers, and turbines. Welding is essential for joining these components together during construction and for repairing them during maintenance.
2. **Pressure Vessels:** Power plants often contain pressure vessels such as boilers and reactors. These vessels need to withstand high pressures and temperatures, requiring precise and strong welds to ensure their integrity and safety.
3. **Piping Systems:** Power plants have extensive piping systems to transport water, steam, fuel, and other fluids throughout the facility. Welding is necessary to connect pipes, fittings, and valves, ensuring leak-proof and efficient operation.
4. **Structural Integrity:** Welding is vital for ensuring the structural integrity of various components within a power plant, including support structures, platforms, and equipment frames. Proper welding techniques are essential to withstand the stresses and loads experienced in operation.
5. **Corrosion Protection:** Power plants are often exposed to corrosive environments due to the presence of water, chemicals, and high temperatures. Welding techniques such as corrosion-resistant alloy welding help protect components from corrosion, extending their lifespan.
6. **Repair and Retrofitting:** Over time, components within a power plant may degrade or become obsolete. Welding is necessary for repairing damaged parts and retrofitting equipment with upgrades or replacements to improve efficiency and performance.
7. **Safety and Reliability:** Quality welding ensures the safety and reliability of power plant operations. Weak or faulty welds can lead to leaks, structural failures, and accidents, compromising the safety of personnel and the environment.

Many general components of power plants require welding during their operational lifespan, including the reheater, header, water wall tubing, superheater, and steam pipes (Stan A David et al., 2015). Fusion welding is integral to the construction, maintenance, and performance optimization of A-USC power plants, supporting their mission to deliver cleaner, more efficient, and sustainable energy solutions for the future. Fusion welding is a welding process characterized by the localized melting and joining of two or more materials to form welds. This method involves heating the materials to their melting point, allowing them to fuse together and solidify upon cooling, creating a seamless joint. Various welding techniques are classified as fusion welding, such as shielded metal arc welding, plasma arc welding, gas metal arc welding, submerged arc welding, electron beam welding, laser welding, gas tungsten arc welding, oxy-fuel welding, and resistance spot welding (Sorrentino, 2017). The research discussed in this thesis focuses on dissimilar welds produced using the SMAW welding process, which is widely used due to its versatility and portability.

2.5 Literature review related to the design and development of SMAW consumables

2.5.1 Shielded Metal Arc Welding

The process of shielded metal arc welding, commonly called stick welding, involves creating an arc between an electrode coated with flux and the work piece. This arc melts the electrode and the base metal simultaneously. The integrity of the weld structure in the Shielded Metal Arc Welding (SMAW) process is influenced by the coatings present on the electrodes. During welding, the flux coating on the electrode melts and vaporizes, releasing gases that shield the weld pool from atmospheric contamination, such as oxygen and nitrogen, thereby stabilizing the arc. The flux also forms a slag layer over the weld bead, protecting it from oxidation and contamination as it cools. SMAW is widely used in construction, repair and maintenance of power plants, pipeline welding, and other industries. It can weld a variety of metals, including stainless steel, nickel-based alloys, and similar and dissimilar metals. SMAW offers several advantages, including its simplicity, portability, and suitability for outdoor and remote welding applications. The schematic diagram is shown in Figure 2.1. However, producing high-quality welds consistently requires skill and experience. Electrode coatings can be categorized as acidic, basic, neutral, or cellulosic, depending on their ingredients. There is very limited literature available in the public domain on the design and development of welding electrode coatings using suitable fillers for the SMAW process for joining dissimilar metals at high temperatures. The development of Shielded Metal Arc Welding (SMAW) consumables for welding dissimilar metals is essential for the widespread utilization of Ni-based alloys in A-USC power plants and need to explore (Siefert et al., 2016). Hence, this research focuses on the design and development of nickel-based electrode coatings to join dissimilar metals in power plants.

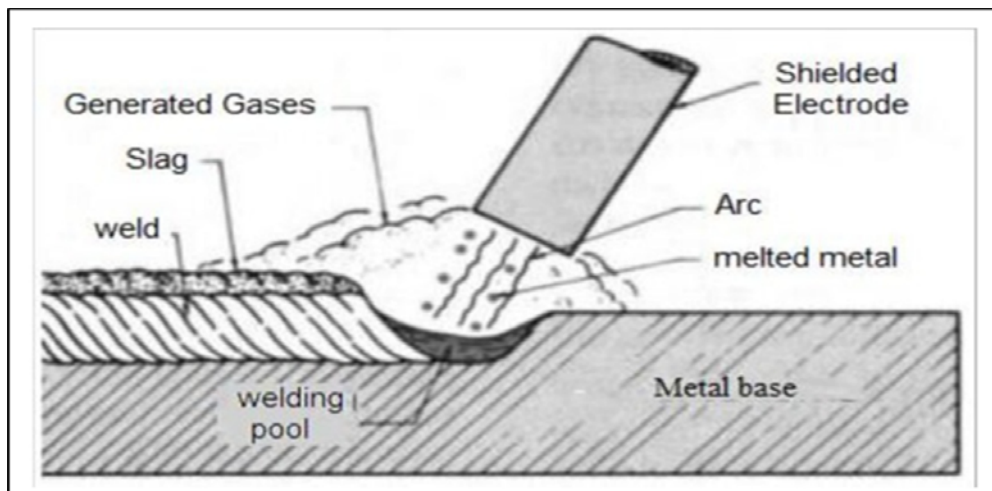


Figure 2.1 - SMAW welding process (Schematic diagram, (Jeffus et al., 1999))

2.5.2 Characteristics and roles of ingredients in electrode coatings

The electrode coating plays a significant role in determining the quality of the weld metal, exerting metallurgical, physical, and chemical effects on the final outcome. Physically, it influences the shape of bead profiles and their relationship, directly impacting the weldments load-bearing capacity. Chemically, it alters the composition of the weld metal, thereby affecting mechanical properties such as tensile strength, hardness, and toughness. Metallurgically, it establishes the grain structure, which in turn impacts the overall properties of the weld metal. Electrode coatings incorporate a variety of minerals aimed at enhancing weld quality. Common minerals such as calcite, silica, rutile, fluorspar, calcinated bauxite, cryolite, strontianite, and magnetite are frequently utilized in these coatings. These constituent minerals serve diverse roles, including stabilizing the arc, forming slag, introducing alloying elements, acting as binding agents, and facilitating movement. Achieving a quality weld necessitates a steady arc, sufficient slag formation, alloying agents, and binding agents tailored to enhance specific properties depending on the application area. Arc stabilizers enhance electrode coatings, thereby promoting stability during the welding process. Slag formers ensure the molten weld pool remains protected from contaminants by producing adequate slag throughout welding. Occasionally, alloying powder is added to electrode coatings to improve the welds' mechanical characteristics. Binding agents are employed to produce a wet mix that adheres to electrode coatings. Additionally, slipping agents are included to facilitate the extrusion process. To prevent electrode coatings from releasing gases that could degrade weld quality, gas-forming materials are utilized to extract these gases from the weld pool (Bhandari et al., 2019, 2016). Previous researchers have extensively detailed the functions of different minerals in electrode coatings and Submerged Arc Welding (SAW) fluxes (Khan et.al, 2020; Mahajan et.al, 2019; Sharma et.al, 2020, 2019). Understanding the characteristics and roles of coating ingredients enables researchers to select appropriate electrode coatings for specific welding applications, ensuring optimal performance and weld quality. Additionally, ongoing research and development efforts aim to further enhance electrode formulations, addressing evolving industry requirements and advancing welding technology.

2.5.3 Effect of electrode coatings on the weld performance

Understanding the influence of electrode coating constituents on physicochemical wetting, structural integrity, weld chemistry, and mechanical properties is essential for researchers aiming to develop electrode coatings. Designing and optimizing welding electrode coatings efficiently is crucial for welding industries to remain competitive globally.

As new alloys emerge and their applications advance, there is a continual demand for formulating electrode coatings in the Shielded metal arc welding (SMAW) process. Obtaining a high-quality weld requires understanding the individual and interactive behavior of electrode coating materials during welding. The physical and chemical properties of flux coating constituents have a significant impact on weld pool composition, playing a vital role in electrode development. The operational characteristics of welding electrode coatings significantly affect weld properties. Previous researchers have reported that minerals in the coating interact with each other through reactions involving slag-metal and gas-metal interactions. Slag formation is essential for the flux-coated electrode during the welding process and plays a crucial role in electrode coating development. The viscosity of slag must be sufficient to cover and shield the weld pool effectively. Additionally, slag viscosity affects its adherence to metal, making it crucial to maintain within an acceptable range during electrode development for optimal weld performance. Calcium fluoride (CaF_2) is utilized to enhance slag fluidity by reducing its melting point and viscosity (Kalisz, 2013; U Mitra and Eagar, 1991). Maintaining slag density lower than that of the molten weld allows it to float above the metal without becoming trapped in it (Natalie et al., 1986). Slag detachability directly impacts weld quality, as improper detachment can lead to defects such as slag inclusions. These defects weaken the weld, reducing its strength and ductility and potentially causing weld failure. Effective slag detachment from the weld bead helps maintain weld integrity and cleanliness, thus ensuring high-quality weldments. Slag detachability is influenced by the physicochemical properties of the minerals used in electrode coatings (Bhandari et al., 2016; Wang et al., 2016). Research has indicated that variation in the coefficient of thermal expansion between the metal and the slag enhances slag detachability (Nadkarni, 1988). Rutile and cryolite, essential components of electrode coatings, enhance slag removal during welding processes (Parmar, 2001; Sham and Liu, 2014). Furthermore, increasing the concentration of acidic oxides like rutile, zirconia, alumina, and silica in electrode coatings has been shown to enhance slag detachability. However, the presence of calcium fluoride negatively affects detachability due to the formation of the cordierite glass phase after interaction with silica (Bhandari et al., 2019, 2016). The arc stability of the SMAW electrode is critical in welding because it directly influences the quality of the welds. When the arc is stable, it maintains a consistent and predictable shape and energy output throughout the welding operation. This stability ensures consistent heat distribution, controlled penetration, reduced spatter, better weld pool control, and minimized defects, leading to higher-quality welds (Niagaj, 2002; Suban and Tušek, 2003). A lower ionization potential refers to the energy required to remove an electron from an atom or molecule, initiating the flow of electricity in the welding arc. When this potential is lower, electrons are more readily emitted, facilitating a steadier and more consistent arc. This stability is crucial for achieving precise control over the welding process and producing high-quality welds (Sham and Liu, 2014). It has been reported that adding coating ingredients such as sodium silicate, rutile, calcite, and potassium silicate enhances arc stability (Natalie et al., 1986). The weld metal forms a superior bead profile, and when the surface tension is low, the slag easily separates from the molten metal. Higher interfacial tension increases the depth of weld penetration (Hazlett, 1957). Calcium oxide (CaO) is added to increase the basicity of flux and decrease the hydrogen content of the weld metal. It also reduces viscosity and improves arc stability, leading to enhanced weld quality and mechanical properties. The primary source of calcium fluoride (CaF_2) is fluor spar, which decreases the density and melting point of flux mixtures. CaF_2 also increases the fluidity of molten metal and removes hydrogen from the molten pool by forming hydrogen fluorides. Silica acts as an agent to improve slag properties when used as welding flux. It enhances viscosity, slag detachability, and surface finish (Kanjilal et al., 2006; Khan and Chhibber, 2020b; Mahajan and Chhibber, 2019; Mills, 2011; Natalie et al., 1986; Qin and He, 2013). Rutile (TiO_2) provides good slag detachability due to the transfer of titanium ions from TiO_2 to the molten weld pool (Parmar, 2001). Cryolite (Na_3AlF_6) is added to improve slag detachability

and facilitate the cleanliness of the weld metal surface for nickel-based consumables (Sham and Liu, 2014). The oxygen content in a weld plays a crucial role in determining its quality and properties. Maintaining the appropriate oxygen content is essential for achieving desired weld properties and avoiding defects. Effectively balancing oxygen levels contributes to the overall quality and durability of the weld. The presence of oxygen in the weld influences the efficiency of transferring elements from the electrode to the weld, removing the most reactive elements from the weld pool and filtering them out as slag. Reports indicate that during welding, chemical reactions take place, leading to the dissociation of various oxides, thereby increasing the oxygen content in the weld. This also significantly influences the mechanical properties (Eagar, 1978). Past studies have reported that slag-metal and gas-metal reactions occur during welding, affecting the weld chemistry and overall weld performance. These studies also proposed a kinetic model for the transfer of elements from an electrode to a molten pool and conducted various experiments to validate the models (Mitra and Eagar, 1984; U Mitra and Eagar, 1991; U. Mitra and Eagar, 1991). Previous researchers have reported that the overall chemistry of the weld metal plays a crucial role in defining the metallurgical and mechanical characteristics of the weld (Davis and Bailey, 1991; Kou, 2003; North et al., 1978; Palm, 1972; Polar et al., 1991). Past studies have examined the effects of fluxes and coatings on the physicochemical properties, wettability, microstructure, weld chemistry, and mechanical properties of the weld (Chen and Kang, 1989; Fox et al., 1996; Jindal et al., 2014, 2013a, 2013b; Waris Nawaz Khan and Chhibber, 2021; Paniagua-Mercado et al., 2005; Petetskii, 1995; Polar et al., 1991; Sharma and Chhibber, 2020, 2019). Nickel-based electrodes were formulated by (Wang and He, 2016) using a flux system based on $\text{CaO-CaF}_2\text{-SiO}_2$. They observed that a lower SiO_2 percentage in the flux coating enhances slag detachability. A mixture of 28.3% CaF_2 and 10.9% SiO_2 achieves optimal slag detachability. (Wang et al., 2016) developed nickel-based electrodes using different flux systems, such as $\text{TiO}_2\text{-SiO}_2\text{-SrO}$ and $\text{CaF}_2\text{-CaO-SiO}_2$, and studied the effect of coating composition on weld quality, mass transfer, and mechanical and microstructural properties. The electrode containing $\text{CaF}_2\text{-CaO-SiO}_2$ demonstrated higher deposition rates, a larger weld bead, reduced spatter, and improved slag fluidity. The $\text{CaF}_2\text{-CaO-SiO}_2$ type welds exhibited better impact strength and mass transfer coefficients than other systems. (Sham and Liu, 2014) developed nickel-based electrodes for power plants using TiO_2 , Na_3AlF_6 , and CaCO_3 as the main constituents. They reported that adding sufficient cryolite improved the weld's cleanliness and slag viscosity. It was also observed that chromium exhibited a 95% recovery rate compared to other low-carbon steel electrodes. The final CSM coating electrodes exhibited enhanced arc stability, extrudability, and welding capabilities. (Qin and He, 2013) developed nickel electrodes using Na_2CO_3 , CaCO_3 , and CaF_2 as ingredients with different ferroalloys and alloying powders, such as Fe-Nb, Fe-Ti, Cr, and Mn, and conducted bead-on-plate experiments to measure the element's mass transfer. They observed an increase in the concentration of alloying elements in the deposited weld. (Singh et al., 2016) investigated how flux ingredients affect element transfer during SAW welding. The researchers measured element transfer in terms of delta quantity and found that flux ingredients, slag-metal reaction, and dilution all influence the amount of element transfer in different welds. A model was developed for element transfer using response surface methodology. (Cruz-Crespo et al., 2010) studied the effect of calcite, fluorite, and rutile on coated electrodes for hard-facing applications. The results showed that increasing the fluorite content in the coating improves both fusion and deposition rates. However, as the fluorite content increases, deposition efficiency decreases. The levels of calcite and rutile present do not appear to alter the fusion behavior of the electrodes. (Jastrzębska et al., 2015) developed a rutile-based coating electrode and conducted experimental investigations on the slag produced from the welds. The results indicated that the higher viscosity of the amorphous silicate phases contributes to improved adhesion of the liquid slag to the weld pool. The high solidification temperature of rutile slag could result in trapping gases within the weld. (Jindal et al., 2014, 2013a, 2013b) used the extreme vertices

design method to develop SAW fluxes based on CaO , Al_2O_3 , CaF_2 , and MgO , and experimentally studied the interactions of the mineral constituents on the mechanical properties and weld compositions. The results reported that increasing the amounts of MgO and Al_2O_3 enhances the ultimate tensile strength, but impact toughness decreases. (Bhandari et al., 2016) developed electrode coatings to fabricate bimetallic welds of steel. The coatings were made up of calcite, fluorite, and silica flux systems with added nickel powder, and the effect of the interactions of the coating constituents on the weld chemistry was studied. It was observed that calcite, fluorite, and silica decreased the nickel and phosphorus content of the weld. The binary interactions between coating constituents increased tensile strength. (Khan and Chhibber, 2020c, 2020b; 2021) conducted investigations into the addition of mineral waste to welding electrodes for offshore applications. The SMAW process was utilized to deposit multipass beads on sDSS 2507 steel. The beads exhibited better microstructure and microhardness, validating the effectiveness of red ochre in developing SMAW electrode coatings. (Mahajan and Chhibber, 2019) developed an electrode coating using a $\text{CaO-SiO}_2\text{-CaF}_2\text{-Al}_2\text{O}_3$ flux system for USC power plant applications. The SMAW process was utilized to deposit multipass beads on P22 plate. An increase in SiO_2 and Al_2O_3 improved the slag detachability of the weld deposits, thereby enhancing bead quality. (Kumar et al., 2023a) investigated the thermal properties of SMAW electrode coating fluxes using regression and neural network modeling. Through an extreme vertices design, 27 flux mixtures were developed based on ternary phase diagrams. Thermal analysis showed weight loss (8.49%–12.25%) and enthalpy changes (-1076.73 to -7786 J/g), influenced by flux composition. Fluorspar improved thermal conductivity, while calcite reduced it. ANN outperformed regression, reducing mean square error by 37% and enhancing predictive accuracy, proving its effectiveness in modeling flux thermal properties. (Kim et al., 2018) investigated the impact of rutile-based electrode coatings on viscosity, wettability, and mechanical properties. Tensile strength and micro-Vickers hardness were analyzed alongside thermo-physical properties. Using 6 wt% Na_2O as a fusing agent, all fluxes exhibited full wetting on a Pt-10Rh plate at 1773 K, ensuring equal coverage. (Bajić et al., 2020) investigated the development of coated electrodes using solid and flux-cored alloyed wire for J55 micro alloyed steel welding. The study compared weld quality, chemical composition, mechanical properties, toughness, and microstructure between classic and specially coated rutile flux-cored electrodes. Results supported replacing solid wire with flux-cored wire due to finer droplet transfer, easier welding, improved joint properties, and higher productivity. Experimental electrode development at IHIS Belgrade demonstrated enhanced welding performance for micro alloyed steel. (Kumar and Chhibber, 2022) investigated SMAW electrode coatings using a $\text{CaO-SiO}_2\text{-CaF}_2\text{-SrO}$ flux system for ultra-supercritical power plant welding. Twenty-one formulations were developed via the extreme vertices technique, and their physicochemical and thermophysical properties were analyzed. XRD and IR spectroscopy examined structural behavior, while regression modeling assessed composition effects. Key ternary mixtures ($\text{CaO-SiO}_2\text{-SrO}$, $\text{CaF}_2\text{-SiO}_2\text{-SrO}$) influenced density, weight loss, enthalpy, thermal conductivity, diffusivity, and specific heat. The study highlighted the critical role of composition interactions in optimizing electrode coatings for strong, durable welds. (Gupta et al., 2024) studied the impact of fluxes in submerged arc welding (SAW), focusing on their role in weld pool shielding, bead geometry, and slag-metal interactions. The study highlights research on optimizing flux compositions to enhance weld quality, mechanical properties, and cost efficiency in steel welding. (Atia and Bamberger, 2020) studied coated electrodes for welding Super Duplex Stainless Steel, analyzing microstructure, tensile, and impact strength. Lower coating basicity reduced oxygen in the weld pool due to interactions between basic and acidic elements. Cooling rates varied by weld zone: Interface > Root > Face, with higher austenite in the face area (slowest cooling) and higher ferrite in the interface (fastest cooling). All welds contained Widmanstätten austenite, grain boundary austenite, sigma phase, and ferrite grains. While sigma phase was unavoidable, secondary austenite could be prevented with

low heat input. Higher austenite improved elongation, while sigma and secondary austenite reduced yield stress. (Kumar et al., 2023b) analyzed SMAW electrode flux wettability for pipeline steels using regression and neural networks. Twenty-seven flux compositions were studied for contact angle, spread area, adhesion, and floatation at 1573 K. Structural analysis (XRD, FTIR, UV-vis) identified flux phases, while ANN outperformed regression, improving predictive accuracy.

2.6 Literature review related to welding of nickel alloy and austenitic stainless steel

The nickel alloy (IN617) and austenitic stainless steel (304H) are used in the form of tubes or pipes in thermal power plants, primarily to transport high-temperature and high-pressure steam. Due to this, their fabrication becomes essential for connecting with various other components of the power plant. These materials are mainly used in high-temperature zones of the reheater, steam header, and superheater panel because of their excellent mechanical properties, creep resistance, and superior corrosion resistance. The primary fabrication technique for joining these dissimilar metals is welding. Welded structures are frequently used in thermal and nuclear power plants due to their high strength, ease of repair, and design flexibility. GTAW (Gas Tungsten Arc Welding) and SMAW (Shielded Metal Arc Welding) processes are the most commonly used methods for joining dissimilar metals in power plants and other high-temperature applications. Researchers are particularly interested in dissimilar welding because of the benefits it provides for joint strength. Reduced costs, more energy efficiency, and more design flexibility are all outcomes of using dissimilar welding. According to research, many industries, including power plants, effectively utilize dissimilar welding. Many industries, including power plants, effectively use dissimilar welding, according to research. Dissimilar welding processes are made more challenging by the large thermal stresses that develop in the weld zone due to variations in the melting point, thermal conductivity, corrosion resistance, and coefficient of thermal expansion of the two metals. Dissimilar metal welds are prone to failure during service when subjected to high-temperature conditions. Various factors contribute to the failure of dissimilar welds, including geometry, welding consumables, welding parameters, welding defects, and residual stresses. Component failure also occurs because materials used for high-temperature applications, such as boiler tubing in power plants, have different creep properties (Kah et al., 2014; Roberts et al., 1985). At high temperatures, dissimilar welds experience carbon migration, metallurgical discontinuities, cyclic thermal stresses, solidification cracking, liquification cracking, and oxidation, all contributing to weld failure (S. A. David et al., 2015). Choosing the welding process and welding consumables is crucial when welding stainless steel and Ni-based superalloys. Failure to do so can result in welded joints with poor microstructural and mechanical properties. Researchers have conducted several studies to determine the appropriate filler or consumable material for dissimilar Ni-based alloy and stainless steel welding (Chandrasekar et al., 2018; Ramkumar et al., 2012). The welding of nickel alloy and austenitic stainless steel is highly challenging due to differences in melting point, thermal coefficient of expansion, and chemical composition. This leads to issues such as solidification cracking, residual stress development, and segregation of elements, which impact the mechanical, creep, and fatigue strength of weld joints (Kasinath Devendranath Ramkumar et al., 2014; Sireesha et al., 2000). Significant issues, such as Nb-rich segregation at the heat-affected zones and weld, arise when welding nickel alloy. The formation of Laves phase significantly influences mechanical characteristics such as hardness, ductility, stress rupture, and strength (Manikandan et al., 2012; Radhakrishna and Prasad Rao, 1997). Previously, many researchers have published various articles related to dissimilar welding of austenitic stainless steel and nickel alloy. Employing the GTAW process and filler wire of 617 (A. H. V. Pavan et al., 2015b) successfully joined 617 and 304H. The author observed that welding parameters were successfully optimized for

the fabrication of dissimilar welds. It was also noted the formation of different zones near the fusion line, such as the unmixed zone, heat-affected zone, and partially melted zone. Fusion zone hardness increases due to the formation of fine $M_{23}C_6$ precipitates compared to the base metal. Many solid solution-strengthened alloys experience various cracking issues. These alloys are often susceptible to solidification cracking, HAZ liquation cracking, and DDC cracking, as detailed by (Akbari-Garakani and Mehdizadeh, 2011; DuPont, 2012) studied the long-term exposure effects on gas turbine made of nickel alloy. They reported microstructural deterioration due to the formation of $M_{23}C_6$ carbides near grain boundaries. It was also observed that continuous formation of carbide precipitates along the grain boundaries decreases the creep rupture strength of the alloy. (Sirohi et al., 2023b) conducted a comparative analysis of welds produced by the SMAW and GTAW processes. It was observed that the weld metal exhibited segregation of Cr and Mo along the inter-dendritic spaces, leading to the development of secondary phases. The solidification mode of the weld metal is austenitic for both joints and enriched with Mo-rich phases known as M_6C and $M_{23}C_6$. The ultimate tensile strength of the weld metal is closer to the base metal for both joints. (Singh et al., 2023) examined the dissimilar weld of nickel and austenitic steel made by multipass GTAW process using the filler ERNiCrCoMo-1 with and without buttering. It was found that mechanical properties and creep rupture of welds were enhanced with buttering. The formation of different zones occurs near the fusion line as results from microstructural analysis. (Ranjbar et al., 2018) studied the carbon migration during welding of IN 617 and A387 steel. They found that nickel-based fillers with higher Ni content decreased carbon migration from base metals with lower chromium content to higher Cr weld metals. Nickel acts as a diffusion barrier and prevents carbon depletion in base metals with low chromium concentrations. (Hosseini et al., 2011) studied the microstructural analysis of IN 617 and SS 310 joints made by the GTAW process. It was observed that welds exhibit a high susceptibility to solidification cracking, which depends on filler material selection. The lowest melting point and Cu-rich secondary phase in SS 310 weld samples cause solidification cracking. Secondary phases caused cracks to form on the partially combined SS 310 base metal side. Similar work was also studied by (Naffakh et al., 2010) with three different fillers, IN617, IN A, IN82, to join IN657 and SS310 and reported that IN filler observed better mechanical properties among other fillers. An experiment was conducted by (K Devendranath Ramkumar et al., 2014) utilizing the PCGTAW and CCGTAW welding processes with fillers ERNiCu-7 and ER2553 to create sound welds of 5 mm in diameter on IN 718 and 316 L. They reported that welding PCGTAW with ERNiCu-7 filler controls laves phase formation and improves mechanical characteristics. Tensile failure also occurred on the SS 316 L base metals. Another study (Kasinath Devendranath Ramkumar et al., 2014) reported the fabrication of IN625/SS304 dissimilar welds using CrMo-3 filler. The welding techniques employed were PCGTAW and CCGTAW. It was found that less segregation as well as low Cr carbide occurred at the HAZ when welding with the PCGTAW technique compared to the CCGTAW process. (SL et al., 2007) reported in their study that titanium and chromium carbide form around the edges of grains and between dendritic regions when different types of steel (IN 690 and SS 304 L) are welded together with fillers IN 82 and IN 52. These precipitates have detrimental impacts on mechanical characteristics. The welding of SS 316 L utilized five different types of fluxes, such as Al_2O_3 , MnO_3 , TiO_2 , SiO_2 , and MnO_2 . Applying all of the fluxes improved the width-to-depth ratio and weld penetration, as reported by (Tseng and Hsu, 2011). In related research, researchers examined how MnO_2 , ZnO , and TiO_2 fluxes affected SS 304 welding. Ultimately, the authors found that TiO_2 and ZnO regulated the penetration depth, with TiO_2 exhibiting less angular distortion (Kourdani and Derakhshandeh-Haghighi, 2018; Nayee and Badheka, 2014) studied ERSS316 L and ERNiCrMo-3 fillers in GTAW and SMAW welding processes to join IN 625 and SS 316 L. They reported that the SMAW samples exhibited a coarser weld microstructure and larger grain structures in the HAZ. The metallurgical and mechanical properties of GTAW samples were superior to those of SMAW

samples. Low heat input and a higher cooling rate give GTAW better mechanical and metallurgical qualities by reducing Nb segregation and producing fine weld microstructures. Obtaining a homogeneous microstructure and mechanical properties during DSW is very challenging due to differences in material properties. A number of metallurgical difficulties can arise, such as carbon migration, unmixed zone transition zones, the formation of type II boundaries, hydrogen-induced cracking (HIC), and hot cracking, as reported by (Ranjbar et al., 2018). In most cases, the partly mixed zone will develop just adjacent to the fusion zone, as shown in Figure 2.2 (a), where the material will liquidate due to the higher temperatures experienced during welding (Ramakrishnan et al., 1972). Figure 2.2 (b) shows that insufficient heat input during the welding of dissimilar metals caused an unmixed zone to occur because the filler metal and base metal melting points are different (Dev et al., 2018; Prabu et al., 2017)

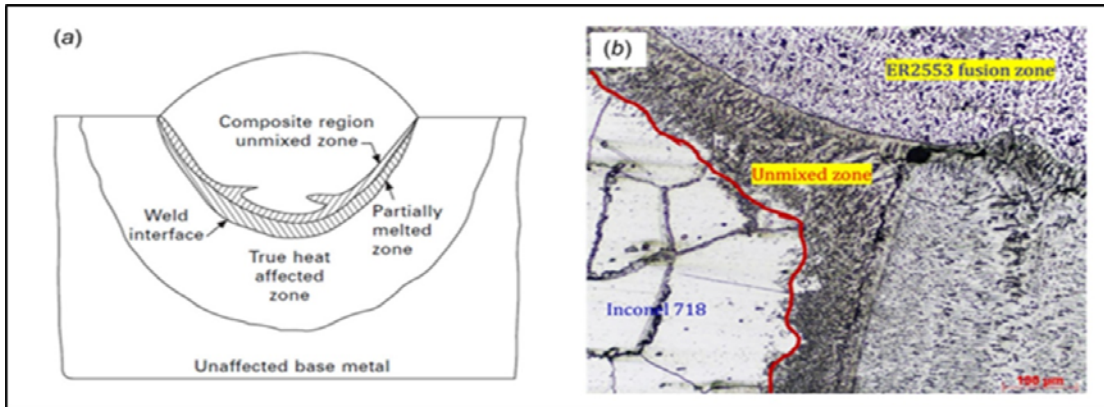


Figure. 2.2 (a) Schematic diagram of welding zones (Shaikh et al., 2011) (b) weld between IN 718 and SS 416 using ER2553 filler showing unmixed zone (Dev et al., 2018)

In the unmixed zone, the base material solidifies without mixing with the weld pool, forming a viscous layer. It is also reported that the mechanical properties of joints are affected by the unmixed zone. The unmixed zone shows peninsula, islands, and beaches-like patterns, as reported by (Soysal et al., 2016). The segregation of the Nb-rich phase at the weld and HAZ zones leads to the formation of the laves phase (Figure 2.3(a,b)). It also highly influences mechanical properties such as strength, ductility, creep, fatigue, and hardness.

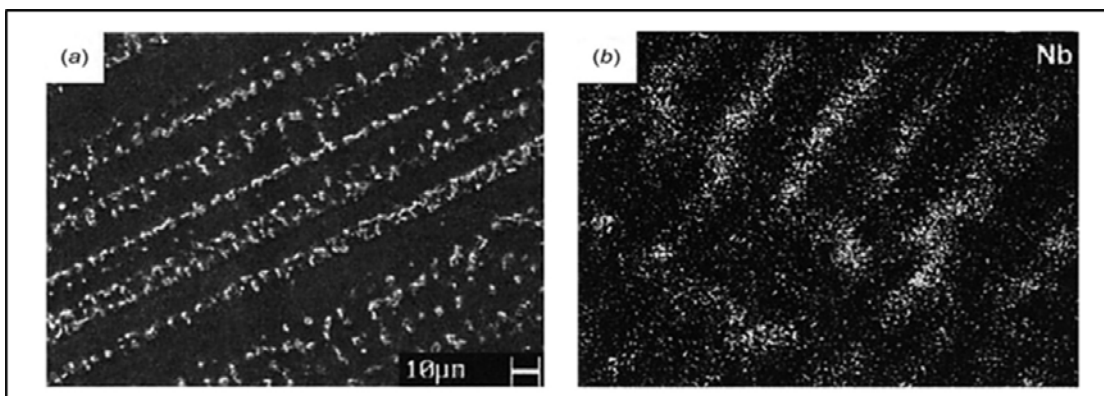


Figure. 2.3 (a) GTAW welded IN 718 weld zone showing the formation of coarser laves phases and (b) X-ray mapping show Nb elements at weld zone (Sonar et al., 2021)

The authors suggest high cooling rates, low weld heat inputs, pulsing procedures, thermal gradients, fillers with a reduced quantity of Nb element, and other methods to decrease the formation of the laves phase (Radhakrishna and Prasad Rao, 1997). Micro cracks can develop in Inconel fusion-welded materials if a liquid film form at the grain boundary of the heat-affected zone (HAZ). This film then undergoes plastic strain during cooling. This

phenomenon is called intergranular micro fissuring (Agilan et al., 2012). After the elements segregate at the borders, liquation of the grain boundaries occurs, which is the main source of intergranular micro fissuring as shown in Figure 2.4 (a-d). When welding at high temperatures, hot cracking occurs at the final stage of the solidification process, including solidification cracking, liquation cracking, and HAZ cracking. Hot cracking is widespread at solidification grain boundaries because of thermal stress and crack-prone microstructures (Shankar et al., 2003). The causes of solidification cracking include welding heat input, composition, grain form size, weld bead size, constraints, and thermal contraction. Reducing mechanical restrictions can help reduce or eliminate solidification cracking. Composition significantly impacts solidification cracking due to the rapid shift from liquid to solid (De Nelson III and Lippold, 1985). The solidification cracking of various materials is illustrated in Figure 2.5 (a-f). Welding Inconel 625 and SS 904 L with different nickel-based filler materials reveals the presence of SGBs and MGBs. Based on the MGBs formation; we can conclude that the fusion zone microstructure is completely austenitic. According to the statement, MGBs often develop in totally austenitic fusion zones that include Ni-rich fillers (Prabu et al., 2017). The author employed a variety of fillers to fuse IN617 and SS310 using the GTAW welding process. The author observed that due to grain growth and cracks, all tensile specimens fail near the heat-affected zone (HAZ) of the SS 310 base material (Hosseini et al., 2011). An important concern when welding different materials, such as nickel-based alloys and stainless steels, is early interfacial creep failure. The failure primarily occurs on the stainless steel side, as it has lower creep strength than nickel alloys. Interfacial failures are associated with problems such as carbide and oxide notching and interfacial stress generation. The interface region's heterogeneity can potentially promote creep failure (Liu.etal.,2019;Zhang.etal.,2021)

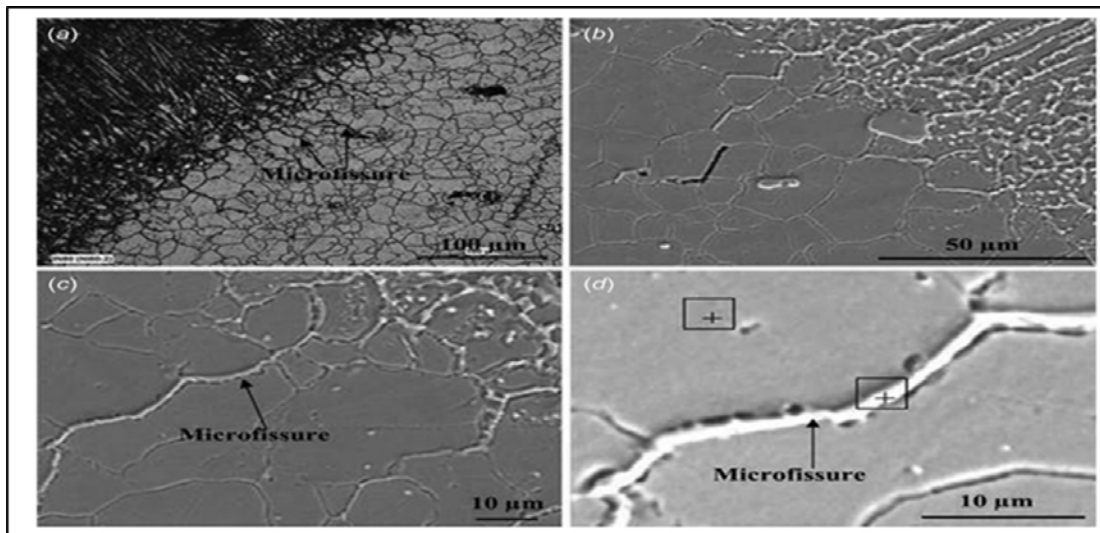


Figure.2.4 (a-d) Micro fissuring effect at the HAZ grain boundaries of solution treated IN 718 (Cao et al., 2009)

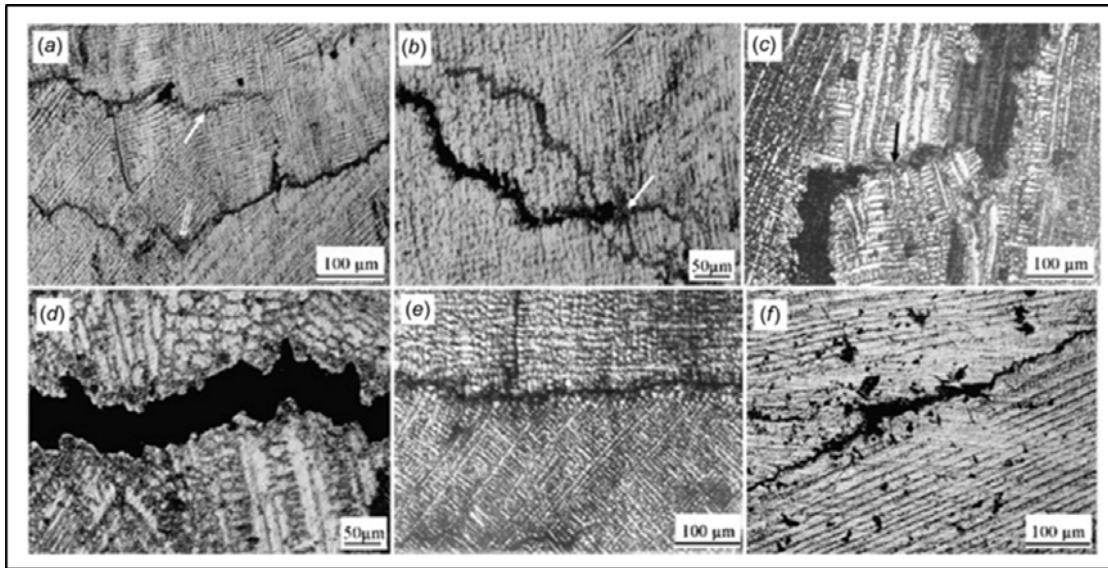


Figure. 2.5 (a) Showing solidification crack in IN 82 weld metal, (b) magnification of (a), (c) showing solidification crack in IN 617 weld, (d) showing magnification of (c), (e) solidification in IN A, and (f) Solidification crack in SS 310 weld (Naffakh et al., 2009)

2.7 Literature review related to hot corrosion in base metal and dissimilar welding

Dissimilar welding in power plants, involving the joining of different types of metals, is a common practice to combine the desirable properties of different materials. However, this technique often presents challenges, including hot corrosion, which is particularly problematic in high-temperature environments such as those found in power plants. Hot corrosion is a form of accelerated oxidation that occurs in metals and alloys at elevated temperatures in the presence of certain contaminants, such as sodium, potassium, and sulfur compounds. These contaminants are typically present in combustion environments due to fuel impurities. When different metals are welded together, they often form a weld zone with a distinct microstructure, which can exhibit different properties compared to the base metals. In thermal power plants, dissimilar welds are often found in boiler tubes, steam turbine components, and heat exchangers. Several factors influence the hot corrosion behavior in dissimilar welds, such as dissimilar welding creating a heterogeneous microstructure in the weld zone, including different phases and grain structures, which can have varying corrosion resistances. Different metals have different coefficients of thermal expansion, which can cause stresses at high temperatures, leading to crack formation and enhanced corrosion. The chemical composition of the weld filler material and the dilution from base metals can create a complex alloy in the weld zone with unique corrosion behavior. Several approaches may be taken to make dissimilar welding less susceptible to hot corrosion. These include the selection of base metals and filler materials that are compatible and have good corrosion resistance. Coatings like aluminides or chromates are used to protect the weld area from corrosive environments. By employing heat treatment processes to relieve stresses and homogenize the microstructure, thereby improving corrosion resistance. Corrosion can also be prevented by minimizing the presence of corrosive species in the operating environment through the use of proper fuels. According to previous researchers' investigations, hot corrosion refers to the oxidation of materials in high-temperature environments caused by applying a thin fused salt layer to their surface. Alkali sulphates that are fused and exhibit excellent thermal stability can readily adhere to substrates at elevated temperatures through the combustion products of gases. The primary factors contributing to the deterioration of oxide scales in oxidizing environments are cracking and spalling (Chatterjee et al., 2001; Rapp, 2002; Yuan and Wang, 2010). High

temperatures, contaminants, and the thermodynamics of corrosion reactions are the three main drivers of hot corrosion in power plant components. The alloys' susceptibility to corrosion might vary depending on the salt type (such as chlorides, sulphates, fluorides, nitrates, etc.). When alkali sulphate salts and alkali chlorides combine, the melting point of the salt is reduced, and the amount of melt increases (Patel et al., 2017). Several elements present in the alloy, such as nickel, chromium, aluminum, and silicon, promote the formation of a protective oxide layer that plays an important role in the alloy's corrosion resistance. Metals and alloys in molten salt have a more complicated corrosion mechanism than those in water solutions. Nickel and iron-based superalloys are the most commonly readily available alloys used in high-temperature applications (Gibbons, 2013). Boilers create fireside deposits that include various contaminants such as chlorides, vanadium, and alkali sulphates. Salt deposits in boiler flue gas dust influence its melting behavior and lead to serious corrosion caused by high temperatures in fossil fuel power plants (Skrifvars et al., 2010). The hot corrosion behavior of IN617 and IN738 at different temperatures with different exposure times was studied. It is reported that corrosion is an endothermic process, raising the temperature causes it to be more spontaneous. IN617 and IN738 exhibited superior resistance to oxidation when oxidized at 700°C compared to when oxidized at 800°C and 900°C. When subjected to high-temperature oxidation, the alloys IN738 and IN617 mainly produce Cr_2O_3 and $\text{Ni}_2\text{Cr}_2\text{O}_4$ (spinel) oxides (El-Awadi et al., 2016). Alloy 617 OCC was studied by previous researchers when exposed to air and salt + gas environment and found that there was no substantial variation in weight seen during air oxidation. On the other hand, experiments conducted in the (salt + gas) atmosphere revealed a significant increase in weight. Furthermore, this weight gain consistently grew as the exposure period increased. The study found that Molybdenum in the alloy and flue gases containing sulphur contributed to the higher corrosion rate (Hari et al., 2019). A study was conducted on the corrosion effects of alloy 617 OCC in salt and (salt + gas) conditions to gain insight into the function of flue gas. The high corrosion rate in the salt + gas environment is mainly attributable to the SO_2 gas found in synthetic flue gas, as evidenced by the sulfur-carrying phases CrS and $\text{Cr}_2(\text{SO}_4)_3$ (Arivazhagan et al., 2019). A fused salt film of Na_2SO_4 and V_2O_5 that was heated to 900°C showed that the oxidation rate went up during the first cycles of Superni-75. Oxide scale spalling was also seen. It was found that more nickel oxides were present in the upper region of the scale, whereas chromium oxides were in the lower area. Both the nickel and chromium oxide scales were consistent, homogeneous, and adherent, which enhanced the superalloys resistance to oxidation (Sidhu et al., 2006). Cyclic hot corrosion studies generate the most intense testing environment, replicating real-life service conditions of superalloy components where breakdowns and shutdowns are common. Cyclic hot corrosion simulates an accelerated environment, similar to real applications, making it the preferred method for studying how different metals and their welds perform during hot corrosion (Arivazhagan et al., 2019, 2012; El-Awadi et al., 2016; Gond et al., 2010; Hari et al., 2019; Prabu et al., 2019). The hot corrosion behavior of dissimilar Monel 400 and SS304 welds when exposed to a salt combination of Na_2SO_4 + 60% V_2O_5 at a temperature of 650°C was investigated. According to the author, when subjected to the mentioned salt combinations, the Monel 400 base metal showed substantially superior corrosion resistance than the weldments. Non-protective scales of FeV_2O_4 and CrVO_4 accelerated corrosion. The ERNiCrFe-3 weld corrosion attack was prevented due to the formation of nickel vanadate $\text{Ni}(\text{VO}_3)_2$ coating (Ramkumar et al., 2014). Another investigation by (Ramkumar et al., 2016) concluded that the fusion zone of weldments made by ERNiCrMo-14 filler exhibited better corrosion resistance than the base metal and weld made by other fillers. The corroded products were characterized by XRD and SEM/EDS. (Arivazhagan et al., 2012) examined the hot corrosion behavior of dissimilar welds of AISI 304 and AISI 4140 when exposed to a salt environment. The findings showed that specimens were subjected to more intense corrosion in the presence of molten salts compared to air oxidation. The samples also showed more corrosion at the weld interface compared to the base metals.

From the above literature survey, it can be concluded that there are very limited research findings available related to the development of Shielded metal arc welding (SMAW) consumables for welding dissimilar metals utilizing Ni-based alloys in A-USC power plants.