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Exploring the Weldability of Austenitic Stainless Steels in Advanced Ultra-Supercritical Power Plant Applications: An Extensive Review

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Abstract

Despite continuous efforts to enhance the operational efficiency of power plants dependent on these fuels, fossil fuels are expected to remain a significant global energy source in the coming decades. India has initiated a mission program to establish Advanced Ultra Super Critical (AUSC) power plants operating at temperature and pressure exceeding 720°C and 30.4kPa respectively. These plants are anticipated to utilize specialized materials with high resistance to corrosion and deformation at elevated temperatures. Among the materials considered, Nickel-base alloys, Creep Strength Enhanced Ferritic (CSEF) Steels and Austenitic Stainless Steels have emerged as the primary candidates. The prime emphasis of this paper is directed towards examining the weldability of Austenitic Stainless Steels utilized in AUSC power plants. It encompasses various aspects such as the choice of filler materials, welding techniques, and the attributes of welds involving both similar and dissimilar metals. The paper provides a comprehensive review of weldability challenges encountered in Austenitic Stainless Steels, including issues like liquation cracking in the heat-affected zone (HAZ), hot cracking, and stress relaxation cracking induced by tramp elements. Additionally, it investigates the performance of different filler wires, namely ER304HCu, ERNiCrCoMo-1, and ERNiCrMo-3, in weld joints involving 304HCu SS tubes, as well as ERNiCrCoMo-1 in dissimilar tube weld joints between 304HCu Stainless Steel and Alloy 617M.

Keywords: Weldability, Austenitic Stainless Steel, AUSC, Advanced Ultra-Supercritical Power Plant.

1.0 INTRODUCTION

Efforts are ongoing to enhance the operational efficiency of power plants that rely on fossil fuels, particularly coal-fired facilities, with the aim of reducing the environmental impact caused by carbon emissions. For this, high operating temperature and pressure are required for boiler applications. This demands for development and utilization of advanced boiler materials. One of the key factors for selection of these materials depends on its ability to be welded easily for fabrication works. As a consequence, the weldability factor plays a pivotal role in determining the suitable materials for modern coal-fired power plants.

Throughout a span of more than five decades, thermal power plants utilizing coal as a fuel source have undergone a remarkable evolution. They have transitioned from subcritical plants, characterized by an operating temperature of 540ºC, pressure of 16.5 MPa, and efficiency of 35%, to the more advanced Ultra Supercritical Power plants. These newer plants operate at a higher temperature of 593ºC, pressure of 24.8MPa, and achieve an improved efficiency of 42%. Continued initiatives are underway in the USA, Japan, and Europe to enhance power plant efficiency up to 45% by augmenting operating temperature and pressure. These specific parameters are being proposed for the implementation of Advanced Ultra Super Critical (AUSC) Boiler Technology. To enhance overall efficiency, extensive efforts have been devoted to the advancement of alloys in USC power plants. Specifically, significant attention has been placed on optimizing Current Creep Strength Enhanced Ferritic (CSEF) alloys and modified Chromium-Molybdenum (Cr-Mo) steels. These materials showcase remarkable physical and corrosion properties, along with superior creep strength at elevated temperatures [1-3].

Through a quantitative methodology, Bhadeshia introduced [4] a range of new steels which are thermally resistive and welding consumables tailored to meet the specific material demands of USC and AUSC power plants. To avoid weld cracking within the heat-affected zone (HAZ), it is essential to implement appropriate precautions during the welding process of Current Creep Strength Enhanced Ferritic (CSEF) steels.

During the welding process, thermal and solidification shrinkage induce stresses that can impact the performance of the weld. These stresses, if not addressed, can remain unchanged and have detrimental effects on the weldment. When exposed to a corrosive atmosphere, the presence of residual stresses can further increase the susceptibility to Stress Corrosion Cracking (SCC) [5-7]. Hydrogen-induced cracking can occur in CSEF materials when there is a combination of residual stress and insufficient preheating [9-11]. Moreover, in certain components like grade 23 (2.25Cr, 1.6W-V-Nb-B) compliant with ASME code, case 2199, the presence of both residual stress and tri-axial stress can lead to the occurrence of reheat cracking. [12-15].

CSEF steels exhibit satisfactory performance up to a maximum temperature of 650ºC. However, when it comes to corrosion resistance, they fall short beyond 620ºC. Furthermore, the maximum allowable stresses of CSEF steels are comparatively lower when compared to austenitic stainless steels and nickel base alloys. In contrast, austenitic steels typically have a composition of 18% Cr and 8% Ni, but they can be modified to contain 25% Cr and 20% Ni for enhanced corrosion resistance and improved strength. These modifications make austenitic steels excellent candidate materials for temperatures above 650ºC, offering superior corrosion resistance, higher strength, and thermal stability at elevated temperatures.

Ni base super alloys are commonly utilized for operating temperatures exceeding 700ºC. Nevertheless, the notable drawback of utilizing nickel and other alloying elements in their composition is the substantial increase in cost, rendering them considerably more expensive than ferritic and austenitic steels. In the United States, various nickel-based alloys are under consideration for implementation in advanced ultra-supercritical (AUSC) power plants. Particularly, Haynes 282 and Inconel 740/740H stand out for their exceptional mechanical properties in comparison to other alloys [9-15].

2.0 WELDING AND WELDABILITY IN COAL FIRED POWER PLANTS

Welding is the process of permanently joining similar or dissimilar materials through the formation of a coalescence or weld bead, with or without the application of heat, pressure, and filler material.

Through the process of fusion welding, the original micro-structure of the parent material undergoes trans-formation due to the application of heat, resulting in the creation of a molten pool known as the Fusion Zone. The Heat Affected Zone (HAZ) is located in close proximity to the Fusion Zone where the material is subjected to heat but does not undergo melting. Beyond these zones, the remaining material remains unaffected by the welding process. As per the Handbook of the American Welding Society, weldability is characterized as the "ability of a material to be effectively welded under the given fabrication conditions, resulting in a well-designed structure that performs adequately in its intended service" [16].

Weldability is influenced by multiple factors, including the composition properties, microstructure, process parameters, and other relevant considerations. Extensive research and analysis have led to the development of several weldability indicators that help characterize the behavior of different welding techniques [17-19]. There are various weldability tests like hot cracking tests which are done during fabrication and tests like toughness, fatigue and corrosion resistance, corrosion resistance tests and tensile and ductility tests done during service [19].

Power generation in India is still highly dependent on coal. Nevertheless, the combustion of coal for power generation is a major contributor to carbon dioxide emissions, which poses significant concerns in terms of climate change. In response, numerous clean coal technologies are being actively developed on a global scale. With the widespread adoption of supercritical boiler technology, including in India, Advanced Ultra Super-Critical boilers (AUSC) have emerged as a modern-day technology utilized to mitigate environmental impact. These boilers attain high efficiency and lead to low carbon dioxide emission. These modern boilers need to be made of advanced materials.

Previously, numerous welding experiments were carried out to determine the optimal combination of process parameters and filler material for welding various components of the predominantly steel boiler. Gas Tungsten Arc Welding (GTAW) was utilized for conducting these experiments [9].

For higher efficiency of power plants using fossil fuel as a source, materials are required to be developed with properties which can withstand higher operating temperature and pressure. A boiler carrying steam at higher pressure consists of tubes and pipes. Tubes typically possess a smaller outer diameter and thin walls, whereas pipes are characterized by larger outside diameters and thicker walls. Pipes can be further categorized into headers, which are comprised of pipes that serve as conduits for steam transportation to the turbine. **Fig. 1** depicts headers composed of thick-walled pipes that are penetrated by multiple tubes [20].

3.0 APPLICATION OF WELDING IN STEAM GENERATORS

High temperature and continuous reaction with steam lead to corrosion in various boiler parts which have detrimental effects. Pipe channels and their bends used in steam generators and continuous joints are to be made of similar and dissimilar materials that require various welding processes to employ for their fabrication. Repair welding is also often used to improve service life of these components mostly. Gas Tungsten Arc Welding (GTAW), is a widely employed welding technique in modern steam generators due to its effectiveness and suitability for the application. Application of welding for the repairment, fabrication and modification of especially austenitic stainless steels have been demonstrated and practiced over few decades by various researchers all over the world [20-33].

3.1 Advanced Boiler Developments

In recent decades, the operating parameters of fossil fuel-fired boilers have undergone changes to enhance the operational efficiency of conventional power plants, aiming to reduce their carbon footprint. The terms "Subcritical," "Supercritical," and

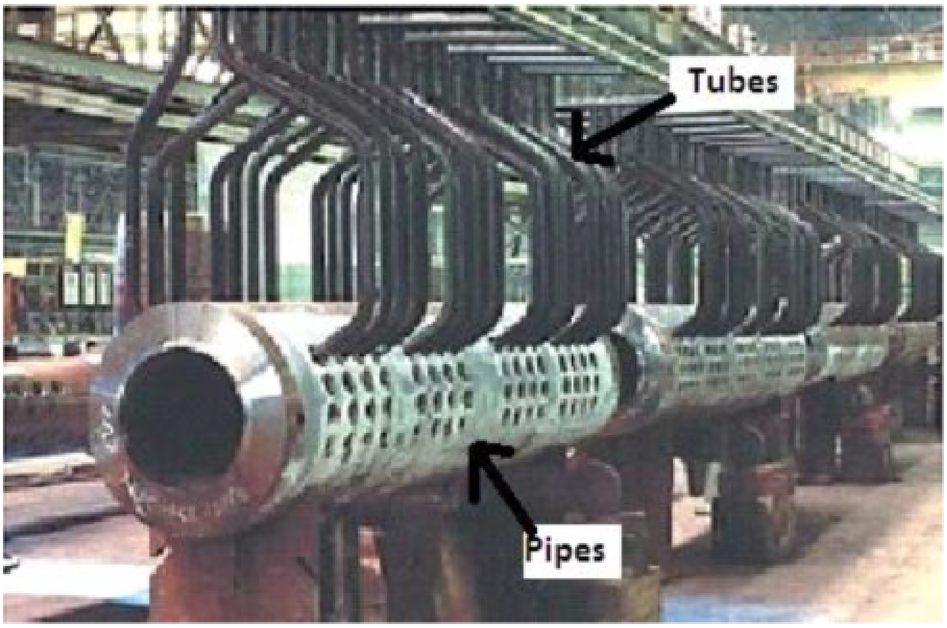

Figure 1 : Headers consisting of pipes penetrated by tubes [32]

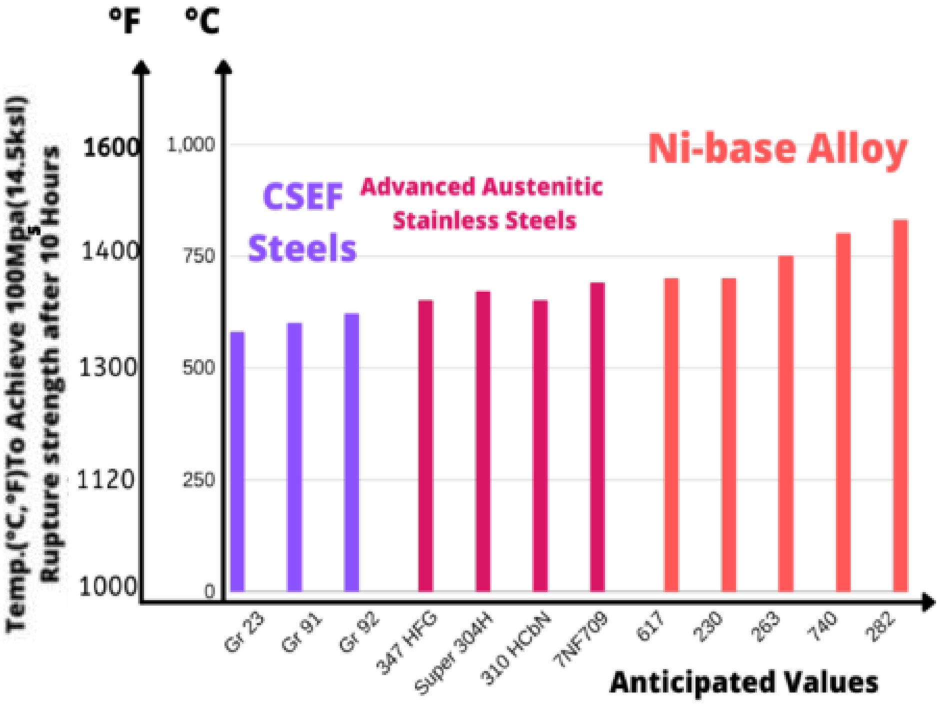

Figure 2 : Average Rupture temperature in 10^5 h for various boiler materials [32]

"Ultra-Supercritical" are used to describe the working conditions inside the power plant's boiler, specifically referring to temperature and pressure levels. The preference is for higher working temperatures and pressures as they contribute to increased plant efficiency, resulting in the need for a relatively smaller amount of coal to generate the same energy output while emitting progressively lower levels of CO_2 [21].

Fig. 2 illustrates the average rupture temperature within 105 hours for various boiler materials [22].

The temperature, pressure and efficiencies for the following boiler types are as follows:

i) Subcritical : <540ºC, 16.5 MPa thermal efficiency of 35%

ii) Supercritical : 565-580ºC, 24.5 MPa thermal efficiency of 38%

iii) Ultra supercritical : 593-620ºC, >24.8 MPa thermal efficiency >42%

iv) Advanced Ultra-Super Critical : >700ºC, >27.5 MPa thermal efficiency > 45%

3.2 AUSC Boiler Materials

AUSC (Advanced Ultra Super-Critical) boiler materials necessitate specific properties such as high creep strength, satisfactory weldability and corrosion resistance. Assessment of weldability is crucial and a prerequisite for the proposed AUSC boiler materials. Initiatives were launched abroad in United States with the objective of achieving boilersteam temperatures exceeding 760°C to attain efficiencies surpassing 45%. Comparable programs have also been initiated in Europe, China, Japan, and India [23-26].

However, there is a global commitment to the shared objective of enhancing the plant efficiency of AUSC (Advanced Ultra Super-Critical) boiler conditions. This endeavour involves both the utilization of pre-existing materials that are suitable for the purpose, as well as the ongoing development of new materials for fabrication.

In the development of components for Advanced Ultra Super-Critical (AUSC) boilers, the key objective is to identify or develop materials that possess exceptional temperature stability and corrosion resistance, allowing them to resist the challenging conditions encountered within the boiler.

Other boiler components, including headers and tubes, need to exhibit high-temperature creep strength, resistance to fireside corrosion, and protection against steam oxidation at elevated temperatures. **Fig. 2** provides an overview of the temperature characteristics of different boiler materials [22, 27, 28]. Furthermore, **Table 1** classifies various coal-fired power plants based on their steam conditions and net plant efficiency. [22].

Nomenclature	Conditions (main steam / hot reheat)	Net Plant efficiency/HHVS
Subcritical	16.5 MPa (2400 lb in^{-2}) 565°C (1050°F) / 565°C / 1050°F	35
SC	≥24.8 MPa (3600 lb in^{-2}) 565 (1050°F) / 579°C (1075°F)	38
USC	≥24.8 MPa (3600 lb in^{-2}) 593°C (1100°F) / 620°C (1150°F)	≥42
AUSC	27.6 - 34.5 MPa (4000-5000 lb in^{-2}) 704 - 760°C (1300 - 1400°F)	≥45

Until about a decade ago, low alloy ferritic steel was commonly employed as the boiler material, capable of withstanding temperatures up to 580°C. Nonetheless, the low Cr-Mo materials demonstrated inadequate oxidation resistance. Consequently, austenitic stainless steels were selected for applications necessitating temperatures exceeding 580°C. However, these materials, characterized by a high coefficient of thermal expansion and low thermal conductivity, are susceptible to thermal fatigue problems in headers, main steam piping, valves, and other components with thicker sections.

CSEF steels exhibit exceptional creep strength at elevated temperatures, along with higher thermal conductivity and a lower thermal expansion coefficient. They are also more cost-effective compared to austenitic stainless steels, making them favourable choices for boiler pipes and headers [29].

For the same design conditions used, ferritic steels with thinner wall thickness for boiler components experience less thermal stresses developed. It also enables a decrease in joint thickness, leading to easier weld joints and reduced welding time [30]. Despite meeting the necessary requirements for AUSC power plants, there have been reported instances of material failures occurring in the Heat Affected Zone (HAZ) of welds after several years of service [31]. This type of untimely failure is commonly termed as Type IV cracking.

The main factor contributing to this failure is the materials' inability to fully restore their original microstructure during fabrication or repair processes. This inability to regain their initial microstructure is the underlying reason behind their exceptional creep properties [32, 33].

According to expert viewpoints [34, 35], the majority of commercially available materials can be utilized for AUSC (Advanced Ultra-Supercritical) technology. These materials, which have been developed for other technologies, are expected to be employed for modern AUSC power plants after undergoing appropriate demonstration to ensure their suitability.

Three main categories of materials are primarily considered for AUSC (Advanced Ultra-Supercritical) technology: CSEF (Creep Strength Enhanced Ferritic) steels, Austenitic steels, and Nickel-based superalloys. CSEF steels demonstrate satisfactory performance within the temperature range of 620°C. CSEF steels with 9% Cr and 12% Cr compositions are frequently employed and demonstrate effective performance below 620°C [36]. Nonetheless, these steels are prone to steam-side corrosion when exposed to temperatures above this threshold.

Moreover, these materials have lower allowable stress levels compared to austenitic stainless steels and super alloys which are nickel based. Austenitic steels, in particular, typically have a base composition of 8 Ni 18Cr and are further adjusted [36] to 20Ni 25Cr to enhance corrosion resistance and increase strength. Additional alloying is done for precipitation hardening and solid solution strengthening [37, 38]. Increased thermal stability, higher corrosion resistance and superior strength above 650°C make austenitic steels excellent for AUSC Boilers. Nickel-based superalloys exhibit thermal expansibility similar to ferritic steels; however, they tend to be more expensive in comparison. In the present work, appropriate welding process parameters would be tried to find out to achieve desired weldability for joining components of A.U.S.C boilers using GTAW process.

3.3 Austenitic Stainless Steels used in AUSC Boilers

Boiler parts such as pipes and headers are susceptible to thermal fatigue cracking. These parts show lower thermal expansion and exhibit better thermal conductivity. However, despite the satisfactory performance of ferritic steels below 620°C with the aforementioned properties, they tend to fail when exposed to temperatures exceeding this threshold. Studies [39] have concluded that Austenitic stainless steels are appropriate for applications at temperatures surpassing 650°C. These steels are derived from a ternary alloy system consisting of iron (Fe), nickel (Ni), and chromium (Cr), characterized by a fully austenitic structure and lacking transformation hardening capabilities [40]. In recent times, researchers have developed a range of heat corrosion-resistant and precipitation-hardenable austenitic steels [39, 41] that demonstrate outstanding creep properties. To enhance high-temperature resistance and corrosion resistance, Chromium and Nickel percentages in austenitic stainless steels are typically increased to 25 and 20, respectively. Additional austenitic stainless steels with improved corrosion properties and higher creep strength have been developed, albeit at a higher cost compared to high-performance austenitic stainless steels. Senba et al. [42] employed a combination of precipitation hardening and solid solution strengthening mechanisms to enhance the performance of these steels. On the other hand, the 304H grade of austenitic steel incorporates additions of Cu, N, and Nb. It falls within the 18Cr-8Ni steel family and demonstrates enhanced strength and superior corrosion resistance [39, 41].

Stainless steel alloys belonging to the 18Cr-8Ni family commonly used include 304H, 316H, 321H, and 347H. Furthermore, advanced stainless steel variants that have been developed include super 304H, 304HCu, 347HFG, XA704, and Tempaloy AA-1. Other austenitic stainless steels are also developed further but they are more expensive as compared to their performance. Major strengthening mechanism like creep strength is developed by the austenitic stainless steels by precipitation hardening and solid solution strengthening. The presence of a uniformly distributed nanoscale copper-rich phase within the grains of 304HCu stainless steel enhances its corrosion resistance and creep resistance. Collaborative efforts with Indian manufacturers have led to the production of 304HCu stainless steel and Alloy 617M for welding similar and dissimilar joints, respectively.

3.4 Solidification in Austenitic Weldments

Substantial progress has been made since the 1970s in comprehending the properties of austenitic stainless steels, including their solidification behavior, segregation patterns, and phase stability of weld characteristics. Understanding of these determines structure, cracking tendency and performance of these steels and its weldments. Depending on the composition of Chromium and Nickel austenitic stainless steels can be fully austenitic (γ) or combination of austenitic and ferritic steels (γ + δ) having duplex microstructures. The residual δ ferrite in the weld refers to the remaining portion that remains after the initial solidification of ferrite and the subsequent solid-state transformation from ferrite to austenite. The quantity of δ ferrite in the weld is commonly assessed using the ferrite number (FN), which is determined based on its magnetic properties, particularly magnetic permeability. It is essential to note that the FN does not provide a direct correlation to the actual percentage of ferrite present. Typically, a Ferrite Number below 10 is generally regarded as indicative of a certain percentage of ferrite [32].

3.5 Ferrite in Austenitic Weldments

The presence of ferrite plays a crucial role in determining the properties and performance parameters of Austenitic Stainless Steels. It has both advantageous and potentially harmful effects when present in austenitic stainless steels. In welded joints, the presence of ferrite helps prevent hot cracking issues. This prolonged exposure to elevated and reduced temperatures can cause spinodal decomposition, which in turn leads to the loss of ductility and the embrittlement of the weld metal.

It is well recognized that austenitic stainless steels are susceptible to hot cracking unless they contain a minimum percentage of 3 to 5% of δ ferrite. Conversely, an excessive presence of δ ferrite, exceeding 5-10%, negatively impacts the properties of the weld joints [32].

4.0 PROBLEMS OF WELDABILITY IN AUSTENITIC STAINLESS STEELS

While Austenitic Stainless Steels are commonly considered weldable with proper control over parameters, they are prone to cracking problems mainly attributed to the presence of impurities like sulphur, phosphorous, and other low melting point elements. Cracking failures can manifest in different forms in Austenitic Stainless Steels, including solidification cracking, liquation cracking, reheat cracking, and ductility dip cracking [40]. To assess the sensitivity of these materials toward weld cracking issues, several weldability tests have been developed [10, 43, 44]. Lippold conducted a comprehensive review [40] on the development of testing procedures for weld cracking. In his analysis, he took into account various factors such as impurity levels, grain size, solidification mode, heat input, and tried to evaluate the tendency and severity of these cracking phenomena. Additionally, attention had to be given to issues like sensitization observed in certain grades of austenitic stainless steels. As a result of sensitization, chromium carbide is formed along grain boundaries, degrading the chromium content in the matrix adjacent to the boundaries, causing intergranular corrosion.

4.1 Hot Cracking and weld penetration

Hot cracking also known as solidification cracking is the phenomenon where low penetration occurs in the austenitic stainless steel during GTAW process which results in cracking [32, 43]. It is predominantly observed in fully austenitic stainless steels and is less common in welds that contain a combination of γ and δ phases [32]. Consequently, it is recommended to have a ferrite number ranging from 5 to 10 in the microstructure to mitigate the aforementioned failure. The most frequently accepted explanation for hot cracking suggests that low melting constituents segregate during the latter phases of weld solidification, resulting in the creation of a liquid phase which has a lower melting point. This liquid phase infiltrates the grain boundaries and subsequently cracks under the influence of thermal and solidification stresses [43].

4.2 HAZ Liquation Cracking

Liquation cracking occurs in the region of the fusion zone as a consequence of a liquid film forming along the grain boundaries. This liquid film weakens the boundary strengths, leading to the occurrence of liquation cracking. The occurrence of these cracks is primarily attributed to the presence of tramp elements such as sulphur (S), phosphorus (P), and metal carbides like titanium carbide (TiC), niobium carbide (NbC), among others. An effective approach to address these cracks involves modifying the composition to encourage the formation of specific ferrite phases at the grain boundaries. Alternatively, reducing the impurity levels to the desired specifications can also help in reducing the likelihood of these cracking issues

4.3 Stress Relief Cracking

These cracks exhibit an intergranular nature and tend to occur specifically within the Heat Affected Zone (HAZ) of stainless steels that are strengthened through precipitation hardening, particularly grades that contain elements like niobium (Nb), titanium (Ti), and others [45]. In industries related to power generation, stress relaxation cracking has been identified in weldments with thick sections, welds that connect stubs to headers, highly restrained weldments, and cold-worked tube bends [46, 47].

4.4 Potential Alloys for AUSC Boilers

The limitations in terms of corrosion resistance and thermal stability at high temperatures observed in 15Cr-15Ni alloys prompted the development of modern austenitic stainless steels like 310H and 347H during the period of 1980s to 1990s. These newer materials were designed to enhance corrosion performance and provide long-term stability. They are characterized by chromium and nickel percentages of 18Cr-8Ni and 25Cr-20Ni respectively, making them well-suited for use as tubing in modern boilers. In addition to 310H and 347H, other commonly utilized advanced grades of stainless steel encompass 347HFG, super 304H, and 310HCbN (also referred to as 310N or HR3C). These alloys have been developed to offer improved properties and meet the specific requirements of various applications. The assessment flowchart is presented in the following diagram.

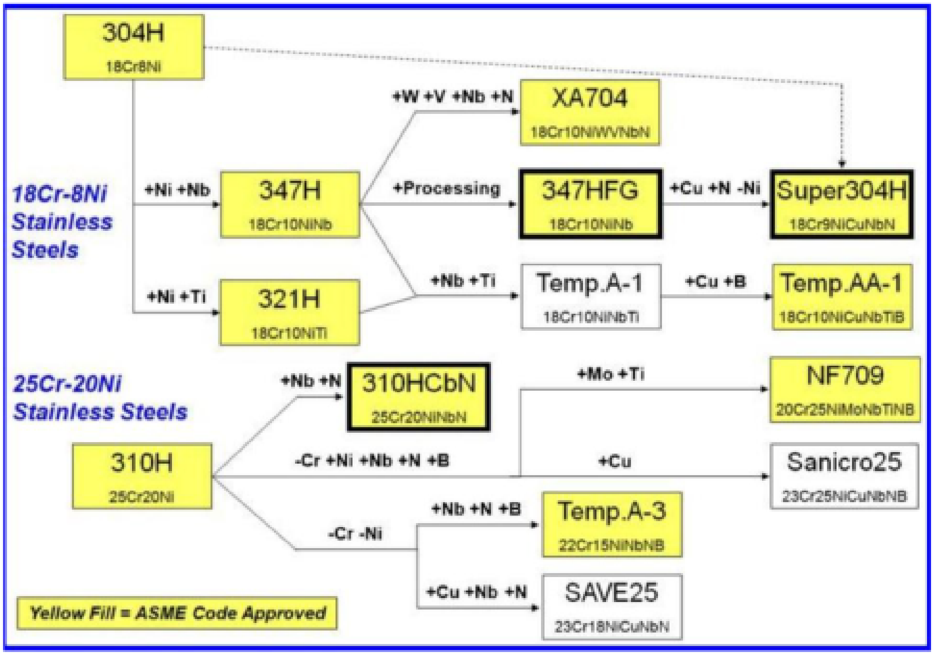

Figure 3 : Development of AUSC Boiler materials [22].

4.5 Potential Alloys for AUSC Boilers in India

In India, significant advancements have been made in the past three decades to tackle performance challenges in power plants through the development of diverse advanced stainless steels. The motivation behind the creation of these advanced stainless steels stemmed from the insufficient corrosion resistance displayed by a preceding generation of high-strength steels, characterized by an approximate composition of 15% chromium and 15% nickel [48]. The aim of the recent advancements in stainless steel technology was to overcome these limitations and enhance the overall performance of power plants in terms of corrosion resistance and other relevant factors.

The careful selection of appropriate materials for high-temperature zones is a critical aspect in the progress of Advanced Ultra-Supercritical (AUSC) technology. The choice of materials should not solely rely on their physical properties but also on their adherence to relevant standards, such as the ASME code, Code Case, or equivalent international codes. These codes consider both the design requirements of components and the commercial availability of the materials. Moreover, while selecting the AUSC (Advanced Ultra-Supercritical) materials for achieving a target steam temperature of 710-720°C, the specific steam temperature needs to be determined by considering several factors and considerations, including:

- Ensuring an average rupture strength of at least 100MPa for prolonged periods at the designated operating temperature of the component.
- Choosing materials with high thermal conductivity and such coefficient of thermal expansion so that it facilitates the reduction of thermal stress is a favourable approach.
- Choosing materials that exhibit excellent formability and weldability to facilitate manufacturing and assembly processes
- Selecting materials that demonstrate exceptional corrosion resistance in both steam and flue gas environments.
- Considering the economic feasibility and industrial availability of the materials for practical implementation.
- Assessing the potential for moderate creep failure interactions to ensure long-term structural integrity.

By considering these factors, suitable materials can be chosen for AUSC applications to meet the stringent requirements of high steam temperatures while maintaining the necessary mechanical properties and durability

The proposed materials for use in AUSC (Advanced Ultra-Supercritical) plants include:

- Grade 23 Steel: This material, with a composition of 2.25% chromium, 1.6% tungsten, vanadium, niobium, and boron, is recommended for water walls according to the ASME code, specifically Case 2199.
- Grade 91 Steel: This material, composed of 9% chromium, 1% molybdenum, vanadium, niobium, and nitrogen, is suitable for tubing purposes as per ASME SA-213 specifications.
- 304HCu Austenitic Stainless Steel: This stainless steel grade, containing 18% chromium, 9% nickel, 3% copper, niobium, and nitrogen, is primarily used for the final stage of super heater tubing. It exhibits stability even after prolonged exposure at 650°C, thanks to the presence of finely dispersed spherical copper precipitates within its austenitic matrix. This material is specified under ASME code case 2328.
- Ni-Based Alloy 617: This alloy, specified according to ASME AB-167, has a composition of 52% nickel, 22% chromium, 13% cobalt, and 9% molybdenum. It is recommended for specific applications in AUSC plants.

These materials have been proposed for their specific properties and suitability to meet the demanding requirements of high-temperature and high-pressure environments in AUSC power plants.

The chemical composition for candidate materials for AUSC Boilers are given in following Table 2 [49].

In 2014, the Indian government commenced research and development endeavors focused on the advancement of materials for AUSC (Advanced Ultra-Supercritical) boilers.This involved a collaboration between three organizations: NTPC Limited and Indira Gandhi Centre for Atomic Research, Bharat Heavy Electricals Limited.

As part of this research, specific welding procedures were developed for both similar and dissimilar weld joints using the AUSC materials. These welding procedures were carefully designed and optimized to ensure the integrity and reliability of the welded joints. **Figures 3 and 4** depict the welding procedures that were developed for these materials, highlighting the step-by-step processes involved. The purpose of this research and development work was to advance the technology and capabilities of AUSC materials for boiler applications in India, with a focus on ensuring the successful welding of similar and dissimilar joints.

Table 2 : The chemical analysis of candidate materials for modern AUSC Boilers [49]

Element	T23 (ASME)	T91 (ASME)	304HCuSS (ASME)	Alloy 617 (ASME)	Alloy 617 (VdTuV 485)	Alloy 617M
Carbon	0.04 - 0.10	0.07 - 0.14	0.07 - 0.13	0.05 - 0.15	0.05 - 0.10	0.05 - 0.08
Manganese	0.10 - 0.60	0.30 - 0.60	1.0 max	1.0 max	0.7 max	0.3 max
Phosphorous	0.03 max	0.02 max	0.040 max	0.015 max	0.012 max	0.012 max
Sulphur	0.01 max	0.01 max	0.010 max	0.015 max	0.008 max	0.008 max
Silicon	0.50 max	0.20 - 0.50	0.30 max	1.0 max	0.7 max	0.3 max
Nickel	-	0.40 max	7.50 - 10.50	44.5 min.	Balance	Balance
Chromium	1.90 - 2.60	8.50 - 9.50	17.00 - 19.00	20.05 - 24.0	20.0 - 23.0	21.0 - 23.0
Molybdenum	0.05 - 0.30	0.85 - 1.05	--	8.0 - 10.0	8.0 - 10.0	8.0 - 10.0
Cobalt	--	--	--	10.0 - 15.0	10.0 - 13.0	11.0 - 13.0
Copper	--	--	2.50 - 3.50	0.5 max	--	0.5 max
Niobium	0.02 - 0.08	0.06 - 0.10	0.30 - 0.60	--	--	--
Titanium	--	0.01 max	--	0.6 max	0.2 - 0.5	0.3 - 0.5
Tungsten	1.45 - 1.75	0.02 max	--	--	--	--
Vanadium	0.20 - 0.30	0.18 - 0.25	--	--	--	--
Nitrogen	0.03 max	0.03 max	0.05 - 0.12	--	--	0.05 max
Aluminium	0.03 max	0.07 max	0.003 - 0.030	0.8 - 1.5	0.6 - 1.5	0.8 - 1.3
Boron	0.0005-0.006	--	0.001-0.010	0.006 max	--	0.002-0.005
Iron	Balance	Balance	Balance	3.0 max	--	1.5 max

Fig. 3 : Indigenously manufactured Boiler tube of SS304HCu, length 6-7m [49]

Fig. 4 : Welding of SS304HCu by GTAW process [49]

5.0 CHALLENGES AND PRESENT CAPACITIES IN INDIA

- Modern technology of AUSC boilers has not yet been developed throughout the world to a great extent.
- Welding, Casting, forging and other fabrication techniques are not standardized and commercialized.
- Boiler and its accessories of this technology have not yet been developed.

5.1 Materials Selection and Development in India for AUSC Boilers

Based on the review of previous literature, it has been identified that SS304HCu and alloy 617M are being employed as AUSC Boiler materials in high temperature zones [50]. The selection of these materials is guided by several criteria, including their inclusion in the ASME Codes/ Code Cases, their proven track record in diverse applications, their commercial availability, and the availability of material properties for design purposes.

6.0 APPROPRIATE PROCESSES FOR WELDING AUSC MATERIALS

Welding operations were conducted on plates and tubes utilizing different conventional processes such as Gas Tungsten Arc Welding, Hot Wired GTAW, and Semi-automated GTAW. These operations specifically targeted alloys such as 617M and SS304HCu. Following successful trial runs, consistent high-quality butt welded joints were achieved in all instances. Optimal process parameters were determined for all the materials, ensuring satisfactory outcomes. Moreover, successful results were obtained for dissimilar welded joints. For the welding of India-Specific 304HCu steel tubes, GTAW process was employed, adhering to the requirements outlined in ASME Section IX [51].

Furthermore, the literature survey indicates that sound fusion welds can be achieved using the GTAW process by utilizing filler materials with superior creep strength compared to the base metal for AUSC Boiler steels [52].

6.1 Filler Materials for AUSC Austenitic Steels

For welding of 304HCu stainless steels, no specific welding consumables are recommended by ASME/AWS codes. As these newer materials like SS 304HCu are not explicitly addressed in various codes and standards, the literature suggests three consumables for welding such austenitic stainless steels: ER304HCu, Ni-based filler material ERNiCrMo-3 (ER 625), and ERNiCrCo-Mo-1 (ER 617). These consumables have been identified as suitable options based on available information. The identified filler materials, namely ER304HCu, ERNiCrMo-3 (ER 625) and ERNiCrCo-Mo-1 (ER 617), were found to possess solid solution strengthening properties and exhibit good solubility with SS 304HCu. Additionally, these filler materials demonstrated corrosion properties that were either superior or comparable to those of 304HCu in the operating temperatures of AUSC boilers. **Table 2** presents comprehensive details regarding the composition of the base materials as well as the corresponding filler materials for AUSC austenitic stainless steels. Post-welding operations, such as Welding Procedure Qualification (WPQ), were conducted and yielded positive results for all the tests conducted according to ASME Sec IX [51].

6.2 Test for Stress Corrosion Cracking

To ensure the chemical compatibility between AUSC Stainless Steels, such as SS 304HCu, and the operating chemicals or fluids in the environment, it is crucial to conduct thorough checks. Special attention should be given to assessing the material's susceptibility in chloride environments. Chloride stress corrosion cracking (SCC) is a significant failure mechanism that can greatly limit the service life of the material, exacerbating its susceptibility to stress corrosion cracking. For the purpose of evaluation of the material's resistance to SCC, experiments were performed on SS 304HCu joints welded using the GTAW process. These experiments involved subjecting the joints to constant load SCC tests in a boiling solution containing 45% MgC [53].

7. USE OF GTAW PROCESS IN POWER PLANT TECHNOLOGY

GTAW process is often extensively employed as a key fabrication method in steam generators in recent times [55]. Austenitic steels like modified 9Cr-1Mo (P 91) steel are commonly used for the construction of components of the power plants, and GTAW plays a significant role in their joining process. However, there are several disadvantages to GTAW, including restricted penetration depth during single pass welding operations, decreased productivity, and a high sensitivity of the weld bead to fluctuations in the chemical composition of the parent metal. Nevertheless, these limitations can be overcome by utilizing a multi-pass welding technique, which promotes surface treatment such as tempering of the welds after every pass.In recent times, there has been significant interest in the use of Activated Flux TIG (A-TIG) for joining power plant components. This welding process is known for its ability to achieve deep penetration and high productivity in a single pass, surpassing the conventional GTAW process. The A-TIG process uses fluxes, where penetration is enhanced by reverse Marangoni flow [55]. In this process, a paste consisting of metallic oxides, such as a mixture of deoxidizers like Si and Ti in the correct proportions, is manually applied in a longitudinal direction along the weld. This application of flux aids in achieving the desired welding characteristics.

8.0 CONCLUSIONS

It is found that GTAW process have been successfully used for welding of similar and dissimilar components of boiler parts especially of AUSC power plants as per ASME codes. Super 304H can be concluded to be more resistant to creep failure, cracking, and stress relaxation cracking than its contemporary alloys based on the substantial weldability data that is now available for this material. Depending on the function, the higher strength of super 304H may necessitate the use of ERNiCrMo-1 which is a nickel based high strength alloy, for achieving the desired results. ER304HCu filler wire can be used for boilers made specifically for India, whereas ERNiCrCoMo-1 filler wire is preferred for its unique welding with 617M alloy tubes in India [49, 51].

9.0 FUTURE SCOPE OF RESEARCH

Considering the continued significance of coal as a major energy source for power plants which are dependent upon fossil fuels in the foreseeable future, the advancement of AUSC (Advanced Ultra-Supercritical) technology holds great promise. The pursuit of higher operating parameters in steam generators, aiming for increased efficiency and reduced carbon footprint, presents a daunting task in the coming years. To prepare for the potential utilization of thicker sections in components, it is worth exploring the inclusion of additional welding processes which have higher deposition rates for example flux cored arc welding. This review paper emphasizes that the technical challenges associated with the weld characteristics of austenitic stainless steels which are employed in modern power plants can be surmounted through a comprehensive and meticulous assessment prior to the utilization of any latest stainless steel grade in boiler components.

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