Phase Transformation Behavior and Stress Relief Cracking Susceptibility in Creep Resistant Steels

THESIS

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Cracking has been reported in newly constructed water wall panels of fossil power plants during startup testing. Both high hardness (exceeding 350 HV) and high levels of welding residual stress have been reported in welds of waterwall panels made of T23 and T24 steels. Stress-relief cracking (SRC) is being considered as a possible failure mechanism during high temperature exposure such as PWHT. High temperature exposure of non PWHT-ed welds of Grade T23 and T24 steels leads to hardening in the weld and coarse-grained heat-affected zone (CGHAZ). It has been suggested that such a hardening mechanism can lead to stress-relief cracking (SRC).

One of the objectives in this study was to investigate the phase transformation behavior and develop continuous cooling transformation (CCT) diagrams in the CGHAZ of Grade T12, T22, T23, and T24 steels. The Gleeble™ thermo-mechanical simulator and a dilatometer were utilized in this study.

The CGHAZ microstructure in Grade T23 and T24 steels was a mixture of bainite and martensite with hardness higher than 340 HV in the studied range of $t_{8/5}$ cooling time from 2 to 50 seconds.
The CGHAZ microstructure in Grade T22 gradually changed from a mixture of martensite and bainite to predominantly bainitic with allotriomorphic ferrite. This corresponded to a moderate reduction in hardness from 340 to 300 HV. In Grade T12 steel, the microstructure of the CGHAZ gradually changed from predominantly martensitic with hardness of 340 HV to bainitic and a mixture of bainite with idiomorphic and allotriomorphic ferrite with hardness lower than 230 HV.

The other objective of this study was to evaluate the susceptibility to SRC in the CGHAZ of T24 steel and in 3-pass welds of Grade T12, T22, T23, and T24 steel tubes.

A Gleeble™-based strain-age cracking test developed at The Ohio State University was modified to better replicate the conditions of PWHT in highly restrained welds and quantify the stress-relief cracking susceptibility in creep resistant steels. In addition to reduction in area and time to failure, the modified test allowed quantification of the stress and strain that cause failure during SRC testing.

The SRC testing of the simulated CGHAZ in Grade T24 steel revealed ductile failure for samples tested at 600°C and SRC failure mechanism for samples tested at 650°C and higher temperatures.

The SRC susceptibility in the tested welds was evaluated based on the maximum PWHT temperature sustained without failure, on the time-to-failure, and on the stress, elongation, and reduction in area at failure. Overall, the welds in Grade T24 and T23 steel had similar resistance to SRC that was higher than in the T22 welds. In terms of time-to-
failure and strain at failure, the T12 welds performed better than or equal to the T23 and T24 welds, but failed at significantly lower stress.

It was concluded that highly restrained welds in Grade T22, T23, and T24 steels that are loaded with high residual stresses may be susceptible to SRC during PWHT above 600°C.
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CHAPTER 1: INTRODUCTION

Steam power plants use heat generated from primary fossil fuels to heat and produce high temperature, high pressure steam [1]. In order to increase efficiency and decrease greenhouse gas emissions in modern boilers, the operating parameters such as the pressure and temperature of steam must be increased. Ultra Supercritical (USC) Boilers operate at pressures at or above 24.8 MPa and temperatures >593°C [2]. Conventional ferritic-bainitic steels such as Grades 12 and 22 do not have high enough creep rupture strength and require larger wall thickness for use in waterwall tubing of USC boilers. Grades 23 and 24 steels were developed to be welded without preheat or post-weld heat treatment (PWHT) in thin-wall components while having superior creep strengths so that higher allowable stresses and higher operating parameters could be experienced without failure [3]. Presently, the service temperature of water wall panels like those made of Grade T23 and T24 steels reaches about 560°C [4].

Grades 23 and 24 steels were developed based on the classic Grade 22 with microalloying additions that provide higher creep rupture strengths and allow higher operating temperatures [5]. Both Grade 23 and 24 have reduced carbon content in order
to help improve weldability. In addition to the lowered carbon content, Grade 23 has additions of tungsten, vanadium, niobium, nitrogen and boron, and reduced molybdenum content. Grade 24 has additions of titanium, vanadium and boron. Vanadium, niobium and titanium are used mainly as precipitation strengthening elements to form MC-type carbides. Boron is used for enhanced creep strength and tungsten may be substituted for molybdenum in order to provide solid-solution strengthening.

Cracking was reported in Grades T23 and T24 welds in water wall panels of newly constructed power plants. Currently investigated failure mechanisms for the cause of cracking include stress-corrosion cracking (SCC) and hydrogen assisted cracking (HAC) [6] [7] [8] [9]. Both failure mechanisms occur when a critical combination of susceptible microstructure, high residual stresses and corrosive environment (exposure to oxygen or hydrogen) is present [8]. Both high hardness (exceeding 350 HV) and high level of welding residual stress have been reported in welds of waterwall panels made of T23 and T24 steels [5] [6] [10]. SCC in such welds may be caused by high oxygen concentrations in the boiler water [7] [9] [11]. A possible HAC mechanism may be related to H₂S evolution during acid cleaning of the waterwalls, or to hydrogen evolution as a product of the Schikorr reaction (magnetite formation on tube ID) at the first stage of service [6] [9].

The objective of this thesis is to evaluate the applicability of two approaches in reducing the hardness in Grade T23 and T24 welds that can potentially be applied for mitigation of the cracking problem in water wall welds. These include controlling the microstructure through weld cooling rate and performing PWHT. As a basis for
comparison, the applicability of these two approaches to welds in Grade T12 and T22 welds is also evaluated.

The applicability of the first approach will be evaluated through development of CCT diagrams for the CGHAZ in Grade T12, T22, T23, and T24 steels that will be supplemented with microstructural analysis and hardness values. The Gleeble™ thermo-mechanical simulator will be utilized to simulate weld cooling histories with cooling times between 800 and 500 C (tₘ₉₅) between 2 and 50 seconds that are representative for GTA girth welds in water wall tubing.

PWHT that would relieve residual stresses and reduce hardness in the weld zone is currently considered for resolving the water wall cracking problem. However, it has been shown that high temperature exposure of non PWHT-ed welds in T23 and T24 steels leads to hardening in the weld metal and coarse-grained heat-affected zone (CGHAZ) [12] [13]. It has been suggested that such a hardening mechanism can lead to stress-relief cracking (SRC). To address this potential problem and determine safe conditions for PWHT the susceptibility to SRC in GTA welds of tested steels will be evaluated and ranked. A Gleeble®-based strain-age cracking test that has been developed at The Ohio State University will be modified in order to better replicate the conditions of PWHT in highly restrained welds and quantify the stress-relief cracking susceptibility in creep resistant steels. In addition to reduction in area and time to failure, the modified test will allow quantification of the stress and strain that causes failure during SRC testing. It is anticipated that this modified test will help better predict SRC susceptibility in creep-
resistant steel welds and help determine safe PWHT temperatures where secondary hardening is minimized.
CHAPTER 2: LITERATURE REVIEW

2.1 Fossil Power Generation

2.1.1 Principles and efficiency

Steam plants use heat generated from primary fossil fuels such as coal, natural gas or oil, and from nuclear fuel in the form of uranium [1]. These fuels contain potential energy that can be released through a combustion process (for fossil fuels) or fission process (for uranium). Steam generators, or boilers, primarily use the energy bound in the fuel to heat and produce high temperature, high pressure steam. Steam is supplied at a certain pressure, temperature and flow rate depending on the application [1]. A steam turbine is a device that turns the energy from steam into mechanical work and is used primarily in electric power production. In order to increase efficiency and decrease greenhouse gas emissions, the pressure and temperature of steam is increased.

2.1.2 Water walls: design, construction / welding, assembly

The furnace is a large enclosed container for fuel combustion. The furnace also is used for decreasing the temperature of the flue gas before it enters the convection pass in
order to prevent particle accumulation and regulate tube temperatures [1]. The convection pass is composed of the superheater, re heater and the economizer. Figure 1 shows a schematic of a coal-fired utility boiler. The furnace and convection pass walls are composed of water wall tubing in order to keep wall metal temperatures within a certain range. Water walls, or water-cooled membrane walls, are composed of tubes joined by a membrane bar that is securely welded to the adjacent tubes and is called a membrane panel. This creates a continuous wall that can transfer radiated heat from the furnace gas to the water or steam-water mixture in the tubes. Membrane walls are gas-tight, so they do not require an exterior casing to contain combustion products. Some membrane tubes may require a refractory lining on the furnace side of the tubes for protection from erosion or corrosion from combustion products. Usage of refractory lining allows the furnace temperature to be increased by reducing heat absorption, but due to maintenance problems its usage should be avoided if possible.
Figure 1: Coal-fired utility boiler [1].
2.1.3 Water walls: working conditions, sources of hydrogen during clean up, start up and operation

Presently, the temperature of water wall panels like those made of Grade T23 and T24 steels reaches about 560°C [4]. When the pressure and temperature of water is increased above 374°C and 22.1 MPa (the critical or triple point for water), the latent heat of vaporization is zero, no boiling occurs and water becomes a supercritical fluid [2] [14]. Sub-Critical Boilers operate where the steam is heated to 540°C and a pressure of 16.5 MPa [2]. Supercritical Boilers operate at higher temperatures and pressures than Sub-Critical Boilers and stay above the critical point of water, operating anywhere between 566-593°C and 25.37 MPa [14]. Ultra Supercritical (USC) Boilers operate at pressures at or above 24.8 MPa and temperatures >593°C. It is important to find materials that have high enough creep and oxidation resistance in order to withstand elevated temperatures in these boilers. Water wall panels are used in USC boilers and must be able to withstand the higher temperatures and pressures required for service.

2.2 Creep in Steels During High Temperature Service

2.2.1 Definition

Creep is a time-dependent, slow and continuous plastic deformation of materials over extended periods of time under a constant load or stress. The temperature is usually elevated above 0.4T_m so diffusion can assist the creep process (where T_m is the melting
temperature) [15]. It is most common that a constant tensile load and temperature is used for creep testing. There are three stages of creep that include the primary or transient creep, the secondary or steady-state creep and the tertiary or acceleration creep. During the primary creep stage, the creep rate decreases with time possibly due to strain hardening. The secondary creep stage is steady-state in nature, so the creep rate is relatively constant and occurs due to the rate of recovery (softening) being equal to the rate of dislocation generation (hardening). The tertiary creep stage is where the creep rate increases with time until sample failure. The homologous temperature is the ratio of the testing temperature (in Kelvin) over the absolute melting temperature. The creep curve shows the time dependence of strain over a given gauge length and the stages of creep may vary depending on the stress and temperature as shown in Figure 2. As indicated by the arrows in Figure 2, as stress and temperature are increased, it is most common that the time to rupture and the amount of steady state creep decreases while the total elongation increases.
Figure 2: Schematic creep curves with varying stress and temperature [15].

2.2.2 Mechanisms

Deformation mechanisms for creep include defect-less flow, glide motion of dislocations, dislocation creep, volume diffusion flow (Nabarro-Herring creep), grain boundary diffusion flow (Coble creep) and twinning [15]. The deformation mechanism map has axes of normalized stress versus the homologous temperature. For engineering creep-resistant steels, this map predicts the dominant deformation mechanism at the beginning of creep given a specific stress and temperature. The deformation mechanism map is divided into fields based on which mechanism is dominant or provides more strain rate than the other mechanisms. Each field has a boundary surrounding it and the boundary line denotes where two mechanisms contribute equally to the rate of creep. These boundaries vary for different materials.
For face-center cubic (FCC) metals and alloys there is a fracture mechanism map that has the same axes of normalized stress versus homologous temperature and details the dominant mechanism that results in fracture in shorter time durations [15]. For creep, there are three fracture mechanisms which include intergranular creep fracture, transgranular creep fracture and rupture.

2.3 Creep Resistant Steels

2.3.1 Design principles

Efficiency of steam power plants may be improved by increasing steam temperature and pressure [15]. With increased efficiency there are reductions in emissions and less fuel is needed so the cost is reduced. In order to increase the steam temperature and pressure, the creep strength of steels must be improved. Design stress of creep-resistant steels is usually determined based on 100,000-300,000 hour creep rupture strength at the operating temperature. The creep rupture strength is the stress required to cause fracture during a creep test within a certain amount of time. The creep rupture strength is greatly influenced by the chemical composition of the steel where certain microalloying additions may either help or be detrimental for the lifetime of the material. Much research has been performed on the effects that microalloying additions have on a material’s creep rupture strength and these results help determine what materials are best suited for high temperature service.
2.3.2 Strengthening mechanisms and alloying

Creep-resistant steels may be strengthened by solid solution hardening, precipitation or dispersion hardening, dislocation hardening and grain boundary hardening [15]. Solid solution hardening involves using substitutional solute atoms such as Mo or W, which have larger atomic sizes than Fe, as solid solution strengtheners. Precipitation or dispersion hardening may strengthen the microstructure by creating different types of precipitate particles in the matrix and at the grain boundaries, usually in a fine dispersion, in order to help stabilize free dislocations. This stabilization of the free dislocations can enhance dislocation and sub-boundary hardening. Dislocation hardening depends on the dislocation density at ambient temperature and may be controlled by changing the tempering temperature. Sub-boundary hardening occurs from lath and block grain boundaries and these can be referred to as elongated sub-grains.

2.3.3 Grades of creep resistant steels, creep-strength enhanced ferritic (CSEF) steels

Some modern creep-resistant steels include bainitic low-Cr steels, tempered martensitic 9-12Cr steels and austenitic steels [15].

2.4 Grade 23 and Grade 24 Steels

The standard ASTM chemical composition ranges for Grade T12, T22, T23, and T24 steels is shown in Table 1 [16]. T23 and T24 were developed based on the
conventional T/P22 and have microalloying additions that provide higher creep rupture strengths and allow higher operating temperatures \([5] [3]\). Both Grade T23 and T24 have reductions in the carbon content to below 0.1 wt\% in order to help improve weldability. In addition to the lowered carbon content, Grade T23 has additions of tungsten, vanadium, niobium, nitrogen and boron, and has a reduction of molybdenum while T24 has additions of titanium, vanadium and boron. Vanadium, niobium and titanium are used mainly as precipitation strengthening elements in the form of MC-type carbides. Boron is used for enhanced creep strength and tungsten may be substituted for molybdenum in order to provide solid-solution strengthening. Vanadium is an alloying addition used to enhance the tensile strength at elevated temperatures and the creep rupture strength \([17]\). Vanadium is also used to improve degradation resistance against temper embrittlement, hydrogen attack and hydrogen embrittlement. In T23, molybdenum is substituted by tungsten as shown in Table 1. Small amounts of boron are added to stabilize the \(\text{M}_2\text{C}_6\) carbides and increase hardenability.
Table 1: Specified ASTM Chemical Composition Ranges for Tubing (wt%) [16].

<table>
<thead>
<tr>
<th></th>
<th>T12</th>
<th>T22</th>
<th>T23</th>
<th>T24</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.05 - 0.15</td>
<td>Max 0.15</td>
<td>0.04 - 0.1</td>
<td>0.05 - 0.1</td>
</tr>
<tr>
<td>Mn</td>
<td>0.3 - 0.61</td>
<td>0.3 - 0.6</td>
<td>0.1 - 0.6</td>
<td>0.3 - 0.7</td>
</tr>
<tr>
<td>P</td>
<td>Max 0.025</td>
<td>Max 0.03</td>
<td>Max 0.03</td>
<td>Max 0.02</td>
</tr>
<tr>
<td>S</td>
<td>Max 0.025</td>
<td>Max 0.03</td>
<td>Max 0.01</td>
<td>Max 0.01</td>
</tr>
<tr>
<td>Si</td>
<td>Max 0.5</td>
<td>0.25 - 1.0</td>
<td>Max 0.5</td>
<td>0.15 - 0.45</td>
</tr>
<tr>
<td>Cr</td>
<td>0.8 - 1.25</td>
<td>1.9 - 2.6</td>
<td>1.9 - 2.6</td>
<td>2.2 - 2.6</td>
</tr>
<tr>
<td>Mo</td>
<td>0.44 - 0.65</td>
<td>0.87 - 1.13</td>
<td>0.05 - 0.3</td>
<td>0.9 - 1.1</td>
</tr>
<tr>
<td>Ti</td>
<td>0.05 - 0.1</td>
<td>0.05 - 0.1</td>
<td>0.05 - 0.1</td>
<td>0.05 - 0.1</td>
</tr>
<tr>
<td>V</td>
<td>0.2 - 0.3</td>
<td>0.2 - 0.3</td>
<td>0.2 - 0.3</td>
<td>0.2 - 0.3</td>
</tr>
<tr>
<td>W</td>
<td>1.45 - 1.75</td>
<td>1.45 - 1.75</td>
<td>1.45 - 1.75</td>
<td>1.45 - 1.75</td>
</tr>
<tr>
<td>Nb</td>
<td>0.02 - 0.08</td>
<td>0.02 - 0.08</td>
<td>0.02 - 0.08</td>
<td>0.02 - 0.08</td>
</tr>
<tr>
<td>B</td>
<td>0.0005 - 0.006</td>
<td>0.0015 - 0.007</td>
<td>0.0015 - 0.007</td>
<td>0.0015 - 0.007</td>
</tr>
<tr>
<td>N</td>
<td>Max 0.03</td>
<td>Max 0.03</td>
<td>Max 0.03</td>
<td>Max 0.02</td>
</tr>
<tr>
<td>Al</td>
<td>Max 0.03</td>
<td>Max 0.03</td>
<td>Max 0.03</td>
<td>Max 0.02</td>
</tr>
</tbody>
</table>
Alloying additions in Grade T23 and T24 steels give them approximately twice the creep strength at typical service temperatures (520-570°C) as Grade T/P22 while maintaining the necessary oxidation resistance for use in superheaters and waterwalls [3].

Grade T23 and T24 steels were developed specifically for use as waterwall tubing in boilers [3].

The initial microstructure of Grade T23 and T24 steels is a banitic-martensitic structure for cooling rates from 0.8 K/s up to 200 K/s and it is supplied in the normalized and tempered state [5].

Grade T/P23 and T/P24 steels may be welded without preheat or post-weld heat treatment (PWHT) in thin-wall components, like in waterwall tubing [3]. However, use of P23 and P24 in thick-wall components like super-heater headers and steam pipes is limited by the weldability as thicker sections are more prone to hydrogen cold cracking and reheat cracking which occurs mainly in the HAZ or weld metal.

2.5 Weldability challenges in Grade 23 and Grade 24 Steels

2.5.1 WM and HAZ hardness

When a fusion weld is made, the significant amount of heat input necessary changes the original microstructure. Weldability is described to be “a measure of the ease with which a metal or an alloy can be welded or joined without degradation that is detrimental to the weldment microstructure or properties during or after welding and for
the duration of intended service” [2]. The two primary regions of a welded joint include the fusion zone (FZ) and the heat-affected zone (HAZ) [18]. The base material (BM) is the area surrounding the weld joint that is not affected by the heat from welding, so it retains the original microstructure. The FZ is the region of the weld that experienced melting and subsequent cooling. The area in between the unaffected BM and the FZ is the HAZ. The HAZ is the region closest to the FZ that is taken to high temperatures where microstructural changes still occur, but the material is never melted. The HAZ has a gradient of microstructure that changes as a function of distance from the fusion boundary as described by Bhadeshia [18]. These regions are classified as the coarse-grained heat-affected zone (CGHAZ), fine-grained heat-affected zone (FGHAZ), partially austenitized zone (intercritical region) and tempered region (subcritical region). The CGHAZ is heated into the austenite phase field of the Fe-C phase diagram where it greatly exceeds the Ac3 temperature and this causes some of the pre-existing carbides to either coarsen or dissolve. Grain growth of the prior austenite grains may occur [18] [19]. The FGHAZ is further from the fusion boundary than the CGHAZ and is also heated above the Ac3 temperature, although not heated to as high an extent as the CGHAZ, and is designated due to its superior mechanical properties over the CGHAZ due to its decreased grain size. The partially austenitized zone or intercritical region is located further from the fusion boundary where the microstructure only becomes partially austenitic during heating. The temperature range in the partially austenitized region is above the Ac1 temperature but below the Ac3 temperature. The tempered or subcritical
region is the region that experienced temperatures below the Ac1 temperature, therefore no austenite was formed on heating.

For Grade T23 and T24 tubes and pipes in the as-welded condition, it is expected that the highest hardness is found in the coarse-grained heat-affected zone (CGHAZ) [20]. Simulated fine-grained heat-affected zones were found to be not susceptible to reheat cracking. So, it was found that it is important to utilize appropriate welding techniques to help avoid creating the CGHAZ in highly stressed areas. T23 and T24 are susceptible to embrittlement due to reheat cracking, but it is claimed that cracking may be avoided given appropriate welding techniques that do not require preheat or PWHT. While the FZ and HAZ are to blame for some of the welding and weldability issues, other issues may be present due to microstructural gradients caused by welding as well as thermal and solidification shrinkage stresses that are formed on cooling which can remain in the material as residual stresses [2]. Different welding techniques may be able to bring about less severe gradients in the microstructure. Large gradients in the microstructure can localize creep strain and this can lead to cracking, like the type IV cracking phenomenon. Residual stresses that are present may increase the susceptibility of a creep strength enhanced ferritic (CSEF) steel weld to issues such as stress corrosion cracking (SCC) when exposed to corrosive environments, reheat or stress-relief cracking and hydrogen-induced cracking.
2.5.2 Possible failure mechanisms

Grade T23 and T24 steels are both low-alloyed heat-resistant steels designed for use in membrane walls, supporting tubes and superheater tubes mainly from coal-fired power plants [21]. Cracking was reported in Grades T23 and T24 welds in water wall panels of newly constructed power plants. Currently investigated failure mechanisms for the cause of cracking include stress-corrosion cracking (SCC) and hydrogen assisted cracking (HAC) [6] [7] [8] [9]. Both failure mechanisms occur when a critical combination of susceptible microstructure, high residual stresses and a corrosive environment (exposure to oxygen or hydrogen) is present [8]. Both have high hardness (exceeding 350 HV) and high level of welding residual stress have been reported in welds of waterwall panels made of T23 and T24 steels [5] [6] [10]. SCC in such welds may be caused by high oxygen concentrations in the boiler water [11] [9] [7]. A possible HAC mechanism may be related to H\textsubscript{2}S evolution during acid cleaning of the waterwalls; or to hydrogen evolution as a product of the Schikorr reaction (magnetite formation on tube ID) at the first stage of service [9] [6].

Slow tensile tests have been performed on T24 in controlled high-temperature water [21]. The effect of heat treatment and water chemistry on Grade T24 SCC susceptibility was investigated. There are three main factors that make a material susceptible to SCC. In order for SCC to occur, a material must first be susceptible to SCC based on its microstructure (which is the result of the material composition and heat treatment). The second factor is that a tensile stress must be present, in the form of an external stress or a residual stress from welding, which exceeds a certain amount given
the sensitivity of the material. For highly sensitive materials, the stress threshold can be close to the yield stress. For less sensitive materials, the stress thresholds can approach the ultimate tensile stress. The third main factor that affects SCC susceptibility is the fluid surrounding the sensitive material that is being stressed. The composition, temperature, and flow conditions of the fluid in the system are important to consider.

The temperature range of highest susceptibility to SCC in oxygenated high-temperature water is dependent on the dissolved oxygen content of the water and the sulfur content of the alloy [21]. This highly susceptible temperature range may be encountered during start-up and shut-down of a steam generator but the normal operating temperature may exceed the susceptible range where SCC is not expected. So, the microstructure may be most susceptible to SCC during ramp-up or ramp-down cycles of the generator.

Using an autoclave where the temperature was kept constant at 180°C, the effect of strain rate, heat treatment and oxygen content on SCC was evaluated for cross weld tensile specimens of Grade T24 [21]. For the strain rate comparison, tensile specimens deformed at the same crosshead speeds but different oxygen concentrations in the fluid showed the same trends of premature failure when subjected to higher oxygen concentrations. For the heat treatment study, it was found that a heat treatment could suppress the SCC mechanism in that instead of a sudden fracture following low deformation, the tested specimens exhibited ductile reduction. For the oxygen content study, it was found that there was a correlation between the oxygen concentration and SCC sensitivity. Lower dissolved oxygen concentrations in the fluid resulted in higher
values of elongation of the cross weld test specimens and longer test durations. Further investigations are necessary to determine the maximum oxygen concentrations at which weld joints in Grade T24 can be used without risk of SCC. The welds in Grade T24 are susceptible to SCC in high temperature water with an increased oxygen concentration.

T24 has been applied in regions of the steam generator since 2000 where it is exposed to high static and thermal stressing [22]. Hot commissioning (testing) was performed at competitors’ plants in 2011 where cracks were discovered in many weld seams where T24 was used and this occurred during the first 300-500 hours of operation. The cause of the cracking was found to be hydrogen-induced stress corrosion cracking (SCC). In order to reduce the risk for weld seam cracking, the production of hydrogen was reduced by eliminating an acid cleaning step, the oxygen content in the water and steam was reduced and the temperature was better controlled. A heat treatment was performed at 450°C on the steam generator in order to reduce residual stresses. After these changes were made, trial operations were performed for a few systems at over 6,000 operating hours. It was concluded that no damage was found in the T24 seam welds due to hydrogen-induced SCC when the hydrogen and oxygen contents were reduced and the temperature was closely monitored.

2.6 Phase Transformations in Steels and CCT Diagrams

2.6.1 Microstructural constituents in steels

The International Institute of Welding (IIW) microstructure classification scheme can serve as the basis for quantification and classification of complex microstructures in
steels [23]. There are principle structure classifications that include ferrite, pearlite, widmanstätten ferrite, bainite and martensite. There are many components to each principal structure classification that describe microstructure details such as shape or location. Table 2 uses information from the IIW microstructure classification scheme to help detail some of the principal structure classifications, corresponding component structures and descriptions of how they appear in the microstructure.
Table 2: Classification Scheme for Microstructural Constituents

<table>
<thead>
<tr>
<th>Principal structure classification</th>
<th>Component structure description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ferrite</strong></td>
<td>Grain boundary primary ferrite</td>
<td>Ferrite veins or polygonal grains aligned with PAGBs</td>
</tr>
<tr>
<td></td>
<td>Allotriomorphic ferrite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polygonal ferrite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ferrite veins</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polygonal primary ferrite non-aligned</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Idiomorphic ferrite</td>
<td></td>
</tr>
<tr>
<td><strong>Pearlite</strong></td>
<td>Lamellar pearlite</td>
<td>Alternating ferrite/cementite lamellae, rapid etching response, low hardness</td>
</tr>
<tr>
<td></td>
<td>Degenerate pearlite</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fine colony pearlite</td>
<td>May be present as a microphase</td>
</tr>
<tr>
<td></td>
<td>Ferrite-carbide aggregate</td>
<td></td>
</tr>
<tr>
<td><strong>Widmanstätten ferrite</strong></td>
<td>Widmanstätten ferrite with aligned microphase</td>
<td>Colonies of parallel ferrite laths (sideplates) with microphases aligned between the laths (like pearlite, bainite, martensite, or retained austenite). Primary Widmanstätten ferrite grows from the PAGBs while secondary Widmanstätten ferrite grows from allotriomorphic ferrite.</td>
</tr>
<tr>
<td></td>
<td>Widmanstätten ferrite sideplates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Widmanstätten ferrite with non-aligned microphase</td>
<td>Widmanstätten ferrite with microphase islands within the PAGs which are cross-sections of Widmanstätten ferrite sideplates that grow from PAGBs below the plane of observation.</td>
</tr>
<tr>
<td></td>
<td>Intragranular</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Widmanstätten ferrite sideplates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Intragranular</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Widmanstätten ferrite plates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Widmanstätten acicular ferrite</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 continued on next page
Table 3: Classification Scheme for Microstructural Constituents (continued)

<table>
<thead>
<tr>
<th>Principal structure classification</th>
<th>Component structure description</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bainite</td>
<td>Bainitic ferrite with aligned carbide</td>
<td>Sheaves of parallel ferrite laths with cementite particles aligned between the laths. Sheaves grow from PAGBs.</td>
</tr>
<tr>
<td></td>
<td>Bainite sheaves</td>
<td>Appear within PAGs, cross-sections of bainite that grow from PAGBs below plane of observation</td>
</tr>
<tr>
<td></td>
<td>Bainitic ferrite with non-aligned carbide</td>
<td>Carbide particles are precipitated between the bainite sub-units.</td>
</tr>
<tr>
<td></td>
<td>Upper bainite</td>
<td>Fine cementite particles precipitated within as well as between bainitic ferrite plates.</td>
</tr>
<tr>
<td></td>
<td>Lower bainite</td>
<td>Sheaves of fine bainitic ferrite plates with aligned carbide which grow from intragranular inclusions</td>
</tr>
<tr>
<td></td>
<td>Intragranular bainite sheaves</td>
<td>Individual fine plates of bainitic ferrite that grow from intragranular inclusions</td>
</tr>
<tr>
<td></td>
<td>Intragranular bainite plates</td>
<td>Very fine interlocking structure formed by multiple impingements of individual bainitic ferrite plates which grow from intragranular inclusions</td>
</tr>
<tr>
<td></td>
<td>Bainitic acicular ferrite</td>
<td>Low carbon martensite, slow etching response, high hardness, may form within the PAGs and smaller colonies may be treated as microphases</td>
</tr>
<tr>
<td></td>
<td>Lath martensite</td>
<td>High carbon martensite with a plate structure and twinned sub-structure</td>
</tr>
<tr>
<td></td>
<td>Twin martensite</td>
<td></td>
</tr>
</tbody>
</table>
2.6.2 CCT diagrams

The chemical composition and cooling rate are two major factors that help determine the microstructure and properties for steels. A continuous cooling transformation (CCT) diagram shows the transformation characteristics for a particular steel and gives the expected microstructures and hardness values after given cooling conditions [6].

CCT diagrams for the base materials of T23 and T24 are shown in Figure 3 and Figure 4, respectively [5]. For T23, bainite forms on cooling around 500-600°C and martensite forms around 300-500°C. For T24, bainite forms on cooling around 400-550°C and martensite forms around 275-450°C. The austenitizing temperatures and times used for T23 and T24 were 1060°C for 15 minutes and 1000°C for 30 minutes, respectively.
Figure 3: CCT diagram for T23 [5].
2.7 Stress-Relief Cracking (SRC) in CSEF steels

2.7.1 Mechanisms and controlling factors of stress-relief cracking (SRC)

In several precipitation-strengthened, creep-resistant steels such as the ferritic alloy steels studied in this research, stress-relief cracking (SRC) is a known cause of many weld failures [19] [24] [25] [26]. SRC is generally intergranular cracking that
occurs in the heat-affected zone (HAZ) or weld metal of welded assemblies during exposure to high temperature service or PWHT. During PWHT, residual stresses may be relieved via plastic deformation of the material [27]. The CGHAZ is known to be the most susceptible region of a steel weldment to SRC. If a material’s microstructure has strong grain interiors that are resistant to plastic deformation along with weak grain boundaries, strain may be localized at the grain boundaries. During the arc welding process the base material closest to the fusion zone reaches temperatures close to the melting point which takes it into the austenite phase field of an Fe-C phase diagram. While in the austenite phase field, pre-existing carbides, carbonitrides, nitrides and some inclusions dissolve into the matrix and the amount of dissolution is dependent on the welding parameters. If dissolution occurs to a great extent, this allows austenite grains to grow to large sizes. During fast cooling, carbon and other dissolved alloying elements may remain trapped in solution while the austenite transforms to bainite or martensite. Upon elevated temperature exposure to PWHT or elevated service temperatures, carbides like M$_3$C, M$_{23}$C$_6$ and M$_6$C may precipitate out and may nucleate on dislocations within grain interiors which causes precipitation strengthening and secondary hardening. These precipitates are typically incoherent with the matrix, are stable at higher temperatures, retard dislocation movement and restrict relaxation of residual stresses. Carbides may also form on the prior austenite grain boundaries. The matrix adjacent to these boundaries may become depleted of alloying elements creating a denuded or precipitate-free zone which is softer and more ductile so strain may be localized in this region.
Some investigations have shown that one SRC mechanism is likely to be due to impurities, especially phosphorus, segregating to grain boundary/carbide interfaces or carbide-free grain boundary areas, especially under high thermal tensile stresses (developed on cooling) [13]. It was found that carbides have higher interfacial energies than grain boundaries [26]. This means it is probable that impurities more strongly segregate to carbide interfaces than to grain boundaries and this leads to embrittlement at the carbide interfaces. The phosphorous concentration was found to be highest at the grain boundary/carbide interfaces, so it is here where intergranular cracking initiates [13]. A precise heat treatment is recommended after the addition of intergranular carbide forming elements like titanium, vanadium or niobium in order to inhibit the formation and growth of carbides growing at the grain boundaries. Without proper PWHT, the strength of the grain boundary/carbide interfaces decreases. This decrease in strength along with the segregation leads to decohesion along these boundaries.

Some main controlling factors for why SRC occurs includes higher material hardness (high thermal stress), slow cooling rates (promotes impurity segregation) and larger grain sizes in the weld metal [13]. In summary, SRC has been said to occur in creep-resistant steels due to a precipitation-strengthened matrix along with a softer Cr- or C-depleted zone that forms along the prior austenite grain boundaries [27] [13]. This is likely caused by coarse, incoherent precipitates; a soft denuded zone and/or elemental segregation. This leads to stress relief not by plastic deformation of the grains, but by cracking along the prior austenite grain boundaries.
PWHT that would relieve residual stresses and reduce hardness in the weld zone is currently considered for resolving the cracking problem, however, it has been shown that high temperature exposure of non PWHT-ed welds in T23 and T24 steels leads to hardening in the weld metal and coarse-grained heat-affected zone (CGHAZ) [12] [13]. It has been suggested that such a hardening mechanism can lead to stress-relief cracking (SRC).

2.7.2 SRC tests – Belgian Welding Institute (BWI)

The Belgian Welding Institute (BWI) SRC test is a Gleeble®-based, isothermal slow strain rate tensile test [20]. In this test, a sample undergoes CGHAZ-simulation. After cooling to room temperature, the sample is heated to the PWHT temperature range between 600 and 750°C. Upon reaching the desired PWHT temperature, the specimen is strained to fracture at a tensile velocity of 0.5 mm/min. The reduction of area is then measured to access the ductility from the fractured specimen. The reduction in area of the tested sample (%RA) is used as a criterion for SRC susceptibility as shown in Table 4.
Table 4: The BWI SRC Test ranking criterion based on % RA for SRC susceptibility

<table>
<thead>
<tr>
<th>RA (%)</th>
<th>Susceptibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5%</td>
<td>extremely susceptible</td>
</tr>
<tr>
<td>5-10%</td>
<td>highly susceptible</td>
</tr>
<tr>
<td>10-20%</td>
<td>slightly susceptible</td>
</tr>
<tr>
<td>&gt;20%</td>
<td>not susceptible</td>
</tr>
</tbody>
</table>

Figure 5 is from the Belgian Welding Institute and shows reduction of area versus the different PWHT temperatures. The as-welded P23 material was found to be the only material which is highly susceptible (5-10% RA) to stress-relief cracking (SRC). It is also shown here that the P23 that received a second thermal cycle (Tp2) was not susceptible to SRC since RA > 20%. The conclusion was made that multiple pass welds in P23 increase the material’s resistance to SRC.
Figure 5: Reheat cracking test results [20].

2.7.3 SRC Tests – Lehigh University (2003)

The SRC Gleeble®-based test from Lehigh University (2003) is a constant displacement stress-relaxation test. A test sample undergoes CGHAZ-simulation and is then heated to a selected test temperature and loaded in tension to a predetermined displacement value corresponding to the 0.2% offset yield strength at the test temperature. The displacement is held constant and the load is monitored as a function of time [27].
The 0.2% offset yield point is found using tensile testing performed in the Gleeble® and it is important to note that a thermal gradient exists across tested samples [28]. The temperature decreases with increasing distance from the center of the sample towards the grips (where at the grips, the material is essentially unaffected). With thermal gradients, microstructural gradients also form. When performing a tensile test, the applied strain may not be concentrated in the region of interest so the acquired data may contain extraneous data not representative of the region of interest. In Nawrocki’s research, the region of interest was the CGHAZ which is produced in the center of the sample, but surrounding the CGHAZ were the fine-grained and tempered regions of the HAZ created due to the temperature gradient. Since only the CGHAZ properties are desired, a dilatometer is placed at the midpoint of the sample and this allows the crosswise displacement of only the CGHAZ to be monitored. The result is a load-displacement curve that is equivalent to a load-lengthwise displacement curve normally obtained from a tensile test. From this load-displacement curve, the 0.2% offset yield point is determined and then the lengthwise displacement at this point is then extracted from the raw data acquired.

Figure 6 shows the PWHT temperature versus the time to failure during stress-relaxation testing where the numbers obtained are the average of four to six tests at each temperature. The stress-relief cracking susceptibility at different PWHT temperatures was measured by the time to failure and exhibited C-curve behavior. The nose of the C-curve, or the shortest time to failure, occurred at 675°C as shown in Figure 6.
Figure 6: Time to failure during stress-relaxation testing for various test temperatures. The numbers within the graph represent the average of four to six tests at temperature [2].

2.7.4 SRC Tests – Lehigh University (2000)

The SRC Gleeble®-based test from Lehigh University in 2000 is a constant load test and has some differences in the procedure from the SRC test discussed in the 2003
paper as discussed in Section 2.7.3. Both papers focused on the same material, HCM2S (T/P 23), although Lehigh’s 2000 paper also compared HCM2S to 2.25Cr – 1 Mo [19].

In Lehigh’s (2000) test, the samples were first subjected to a weld thermal simulation cycle for HAZ-simulation. The peak HAZ temperature used was 1315°C (1350°C in Lehigh 2003). The preheat temperature was the same at 93°C. For this test, different energy inputs of 2, 3, and 4 kJ/mm were compared for each sample.

A uniaxial load is imposed on the sample as the sample cools from the peak HAZ temperature and is held for the duration of the test to simulate the residual stresses present in an actual weldment. The load is held constant and not the stress because the stress will change as the cross-sectional area of the specimen changes. The initial stress level to test the HCM2S was chosen to be 325 MPa based on the yield strength of the alloy at ~650°C. The yield strength of the CGHAZ of this alloy at the test temperature was unavailable, therefore this value was chosen by Lehigh (2000) because 650°C is near the middle of the test temperature range. This constant load test is more severe than a constant displacement or a stress relaxation test as the load is not allowed to relax. After cooling to room temperature, the sample is then subjected to a simulated programmed PWHT temperature (between 575-725°C) and held at a constant temperature and load (that corresponds to the initial stress level) until failure. A schematic of the test cycle is shown in Figure 7. The time to failure was taken to be the time when the PWHT temperature was reached to the time of rupture and the ductility was determined as the reduction in area during PWHT. Figure 10 shows Lehigh’s results for the PWHT temperature as a function of time to failure.
The ductility is measured as the percent reduction in area and is used to predict the susceptibility of the samples to stress relief cracking. Figure 8 shows the reduction in area measurements as a function of PWHT temperature at energy inputs of 2, 3, and 4 kJ/mm for both 2.25Cr-1Mo and HCM2S at an initial stress level of 325 MPa. Figure 9
shows the reduction in area as a function of PWHT temperature at an energy input of 2 kJ/mm along with a lower initial stress value (270 MPa) for 2.25Cr – 1Mo.

Figure 8: Lehigh’s (2000) reduction in area as a function of PWHT temperature at various energy inputs [19].
Figure 9: Lehigh’s (2000) reduction in area as a function of PWHT temperature for an energy input of 2 kJ/mm along with the lowered stress values for 2.25Cr – 1 Mo steel [19].
Figure 10: Postweld heat treatment temperature versus time to failure for an energy input of 2 kJ/mm along with lowered stress values for 2.25Cr – 1Mo steel [19].

Some conclusions found by Lehigh (2000) were that every failure occurred in the CGHAZ, HCM2S was shown to be more susceptible to SRC than 2.25Cr – 1Mo and that HCM2S showed no clear variation in ductility with PWHT temperature (Figure 9).
2.7.5 SRC Tests – Seth Norton’s The Ohio State University (OSU)

A schematic of the cylindrical round-bar specimen dimensions used by Seth Norton on Ni-based alloys at OSU is shown in Figure 11.

Figure 11: OSU schematic illustration of the sample dimensions [29].
Figure 12: OSU schematic illustration of thermal and mechanical control for HAZ and PWHT simulation [29].

Seth Norton’s The Ohio State University SRC Test was developed for Ni-based alloys and served as the basis for developing the current OSU SRC Test performed in the research detailed in this thesis for creep-resistant steels like Grades T12, T22, T23, and T24. To help avoid confusion between Seth Norton’s version and the more current OSU SRC Test developed, Seth Norton’s name will be referred to whenever his test is discussed. Seth Norton’s OSU SRC Test is a constant displacement Gleeble®-based test [29]. In his test, a sample undergoes HAZ-simulation. Upon cooling from the peak
temperature to below 1100°C, the stroke begins moving at a rate of 0.1125 mm/min (Waspaloy) and 0.05625 mm/min (Alloy 718) and loads the sample in tension as the sample continues to cool. A schematic of this application of the stroke and the temperature control is shown in Figure 12. For both tested alloys the stroke / displacement, or total amount the sample is deformed, was 0.45 mm. By applying load upon cooling, yield strength magnitude residual stresses are said to be present at room temperature. The stroke rate and the total stroke distance used for the development of residual stresses on cooling from the peak HAZ temperature was determined through trial and error.

After the HAZ-simulation, the sample is heated to and held at the PWHT temperature for a predetermined period of time between 0-4 hours and the stroke/displacement is held constant at the level applied during the HAZ simulation [29]. Upon completion of the PWHT, the sample is cooled down to room temperature. The sample diameter is measured with Vernier calipers at the center the gage section without removing the sample from the Gleeble®. The sample is then reheated to the PWHT temperature and the jaws are stroked at 1 mm/min until sample failure. Upon failure the test is stopped and the reduced sample diameter at the fracture surface is measured. Each half of the fractured sample is measured at three places and the average of the six readings is recorded as the reduced diameter of the sample.
Figure 13 gives an example of a typical data acquisition plot for the HAZ and PWHT simulation of a Waspaloy bar.

The yield strengths at different PWHT temperatures for each sample was derived from the data acquired in the hot ductility portion of the test and these values are shown in Table 5 and Error! Reference source not found.. There were three channels of feedback recorded from the Gleeble® for the HAZ and PWHT simulations as well as for the hot ductility portion of the test. These three channels were the temperature at the thermocouple, the axial load and the stroke distance. The force measurements showed the increased residual stress after cooling to room temperature from the HAZ simulation, the
minimum force after thermal expansion caused by heating to the PWHT temperature and the change in force as the sample precipitation hardened. The axial force measured by the transducer was converted to engineering stress with units of megapascals (MPa). From the hot ductility test data was found regarding the yield strength, the tensile strength and the time to failure.

Table 5: OSU Waspaloy Hot Ductility [29].

<table>
<thead>
<tr>
<th>PWHT Temp (°C)</th>
<th>PWHT Time (hr)</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>% Reduction in area</th>
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<td>624</td>
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Peak HAZ temperature of 1240°C and 20 second hold time in Waspaloy samples

Waspaloy Regression Model \( (R^2 = 0.92) \)

\[ 0.355(T/100)^2 + 0.005t^2 - 5.85(T/100) - 0.490t + 0.0577(T/100)t + 24.2 \]

\( T = \) PWHT temperature
\( t = \) PWHT time
By comparing the obtained yield strength values from Table 5 with the stress values in Figure 14, it is shown that the residual stresses built up during cooling in the HAZ simulations on Waspaloy are on the order of magnitude of the yield stress for the material.

![Waspaloy Stress Response](image)

Figure 14: OSU residual stress developed in Waspaloy HAZ simulations (1240°C peak, 0.1125 mm/min stroke rate) [29].
Table 6: OSU Alloy 718 Hot Ductility [29].

<table>
<thead>
<tr>
<th>PWHT Temp (°C)</th>
<th>PWHT Time (hr)</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>% Reduction in area</th>
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<td>818</td>
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<td>424</td>
<td>460</td>
<td>81.9</td>
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</table>

Peak HAZ temperature of 1184°C and 15 second hold time in Alloy718 samples

Alloy 718 Regression Model ($R^2 = 0.91$)

$$0.448\left(\frac{T}{100}\right)^2 + 0.004t^2 - 6.42\left(\frac{T}{100}\right) - 0.180t + 0.200\left(\frac{T}{100}\right)t + 23.3$$

$T =$ PWHT temperature

$t =$ PWHT time

Much like for the Waspaloy material, by comparing the obtained yield strength values from Table 6 with the stress values in Figure 15 for Alloy 718, it is shown that the residual stresses built up during cooling in the HAZ simulations are on the order of magnitude of the yield stress for the material.
The ductility of the materials was measured by the reduction in cross sectional area. This data, as shown in Table 5 and Table 6, was used to develop a multivariate polynomial for calculating the ductility as a function of PWHT temperature and time. Waspaloy has a lower ductility minimum that occurs at higher temperature as compared to Alloy 718 as shown in Figure 16 for no PWHT and Figure 17 for 3 hours PWHT.
Figure 16: OSU comparison of ductility behavior in Waspaloy and Alloy 718 regression models for no PWHT [29].
Figure 17: OSU comparison of ductility behavior in Waspaloy and Alloy 718 regression models at 3 hours PWHT [29].
3.1 Materials

In order to increase efficiency in modern boilers, operating parameters such as temperature and pressure must be increased [5]. In order to achieve higher operating parameters, steels with higher creep strength and higher allowable stresses were developed. Ferritic-bainitic steels such as Grades T12 and T22 require post-weld heat treatment (PWHT) after welding in order to reduce maximum hardness values to below 350 HV. These steels do not have high enough creep rupture strengths for use in waterwall tubing of Ultra Supercritical (USC) boilers. Grades T23 and T24 were developed to have higher creep rupture strengths and lower hardness values after welding. The respective compositional ranges of each alloy are shown in Table 1.

Grades 23 and 24 steels were developed based on the classic Grade 22 with microalloying additions that provide higher creep rupture strengths and allow higher operating temperatures [5]. Both Grade 23 and 24 have reduced carbon content in order to help improve weldability. Preheating and PWHT are no longer necessary for reduction of hardness in the heat-affected zone (HAZ) of these steels. In addition to the lowered
carbon content, Grade T23 has additions of tungsten, vanadium, niobium, nitrogen and boron, and has a reduction of molybdenum while T24 has additions of titanium, vanadium and boron. Vanadium, niobium and titanium are used mainly as precipitation strengthening elements in the form of MC-type carbides. Boron is used for enhanced creep strength and tungsten may be substituted for molybdenum in order to provide solid-solution strengthening.
3.2 Sample Preparation

3.2.1 CGHAZ-simulated samples for The OSU SRC Test and the BWI SRC Test

All tubing materials were received in the normalized and tempered condition. Four inch long dogbone samples for CGHAZ-simulation and SRC testing were extracted along the tube axis of Grade T24 tubes as shown in Figure 18. The gauge section cross sectional area of the T24 dogbone samples was initially about 3.007 x 10^5 m².

Figure 18: Schematic illustration of samples for BWI SRC and OSU SRC testing
The Gleeble® 3800 thermomechanical simulator was used to simulate the CGHAZ, the most susceptible region of a weldment to stress-relief cracking, by resistively heating the sample at a rate of 100°C/sec to a peak temperature of 1350°C and then free-cooled with a t₈/₅ ≈ 12-13 seconds. To prevent oxidation, the test chamber was evacuated to a pressure of 5x10⁻³ torr. Low-force jaws allow free thermal expansion and contraction of the sample on heating and on cooling, therefore limiting induced stresses during the thermal cycle. The cooling rate or t₈/₅ time was controlled by a combination of the type of grips used and the spacing between the grips. Water cooled grips were used to provide electrical contact and heat transfer. Free cooling occurs by conduction through the sample to the water cooled grips.

3.2.2 3-pass welded samples for OSU SRC Testing

All 3-pass gas tungsten arc welded (GTAW) tubing materials were received in the normalized and tempered condition. The 3-pass weld design is shown in Figure 19. Similar to the CGHAZ-simulated samples, four inch long reduced section dogbone samples were extracted from waterwall tubing along the tube axis as shown in Figure 18, although the weld root was kept intact and was unmachined as shown in Figure 20. It should also be noted that the samples were machined in such a way in that the weld root is positioned in the middle of each sample.
Figure 19: 3-pass weld design

Figure 20: 3-pass weld sample, weld root not machined
3.2.3 Cylindrical samples for CCT diagram development

Tubes were provided in the normalized and tempered condition of Grades T12, T22, T23, and T24. Several cylindrical samples of 6 mm diameter were electrical discharge machined from each tube, followed by centerless grinding. Copper grips and water cooled jaws were used to provide electrical contact and heat transfer. Free cooling occurs by conduction through the sample to the water cooled grips. A dilatometer measures the dilation, or volume change of the sample diameter, in order to study the phase transformations during the CGHAZ-simulation thermal cycle. The cooling rate is different for each cylindrical sample and is controlled by the distance between the copper grips which is called the free span. The contact area between the copper grips and the cylindrical samples was kept constant for all free spans from 10 to 40 mm and for free spans from 45 to 70 mm. In order to keep the contact area constant, each sample was machined to an appropriate length. For free spans of 45 to 70 mm, the contact area was halved from the samples with free spans between 10 and 40 mm. This is important to note as this difference in contact area of the sample with the copper grips may have a slight effect on the start and finish transformation temperatures found in this study.
3.3 Thermocouple and extensometer setup

A Type K (chromel-alumel) thermocouple was spot-welded onto the center of each dogbone sample in a plane perpendicular to the longitudinal axis as shown in Figure 21. The thermocouples were used to monitor the thermal history as well as provide program feedback. Each thermocouple wire is covered with fiberglass insulation in order to prevent short circuiting.

![Thermocouple and extensometer placement on dogbone samples](Image)

**Figure 21: Thermocouple and extensometer placement on dogbone samples, gauge length and restraint distance shown**
An extensometer was used to measure the strain being applied to the sample during testing. Two wires were spot welded onto each sample, each at a position of 3 mm from the centerline of the dogbone sample. These two wires are cut to a height of about 1 mm tall (or less) so they will hold rigid and will not deform when the ceramic extensometer rods are pressed up against the sample while applying pressure to the wires as shown in Figure 21. The distance between these wires, which is the gauge length, is 6 mm. The gauge length was measured using vernier calipers for each sample tested and was taken into account for strain calculations.

The 6 mm gauge length was determined by performing temperature distribution tests where one thermocouple was placed at the centerline of the sample and other thermocouples were placed at certain distances away from the centerline. It was found that within 3 mm to each side of the centerline the temperature varied no more than 6°C when held at temperatures between 550 and 750°C. Based on this study, it was concluded that a 6 mm gauge section is within an acceptable range for elevated temperature tensile testing and SRC testing.
3.4 **Yield Strength Determination – Room Temperature Tensile Test**

A room temperature (RT) tensile test was performed using The Gleeble® 3800 for a CGHAZ-simulated Grade T24 dogbone sample as well as for each 3-pass weld dogbone sample of Grade T12, T22, T23, and T24 in order to determine the approximate yield strengths for use in the OSU SRC Test. The tensile test was performed using mechanical jaws and stainless steel hot grips at a rate of 0.5 mm/min until failure. Failure occurred in the weldment region for all samples except for Grade T22 where the break was outside the 6 mm gauge section, so failure occurred in the base material region.

3.5 **The OSU SRC Test**

The strain-age cracking test developed at The Ohio State University was modified in order to better replicate the conditions of PWHT in highly restrained welds and quantify the stress-relief cracking susceptibility in creep resistant steels. In addition to reduction in area and time to failure, this modified test allows quantification of the stress and strain that cause failure during SRC testing. This test utilizes the Gleeble® 3800 thermo-mechanical simulator. This procedure is meant to replicate post-weld heat treatment (PWHT) or high-temperature service in order to help predict safe PWHT conditions. The restraint distance, or distance between the serrated stainless steel grips was 42.5 mm and the gauge length is approximately 6 mm, as shown in Figure 21.

The OSU SRC Test uses mechanical jaws so that a tensile stress may be applied to the sample and a set of serrated stainless steel hot grips. The dogbone samples will
have a simulated-CGHAZ or a 3-pass weld as shown in Figure 22 and Figure 23, respectively. Sample preparation of the simulated-CGHAZ samples and 3-pass weld test samples was described in sections 3.2.1 and 3.2.2, respectively. The thermocouple and extensometer setup was described in section 3.3. Using force control mode at room temperature, the test sample is loaded with 90% of the CGHAZ yield strength (0.9YS) in order to simulate high level welding residual stresses. Test samples were loaded at a rate of 2.93 kN/min for the CGHAZ-simulated samples and at a rate of 0.98 kN/min for the 3-pass weld samples. Recall that the yield stress was determined from the room temperature tensile test as described in section 3.4. Once the test sample is loaded to 0.9YS, the test switches from a force control mode to a displacement control mode and the stroke is fixed in order to simulate a high level of weld restraint. Thus, The OSU SRC test reproduces the worst case scenario of high level residual stresses in highly restrained welds of water wall panels.

PWHT is simulated under constant displacement mode by heating the test sample at a rate of 200°C/hour and holding for 8 hours. If no failure occurs in the 8 hour period, the sample is strained to failure at a rate of 1 mm/minute. The test outputs are time to failure, stress at failure, strain at failure and reduction in area. The strain over a uniformly heated gauge section is monitored using a strain gauge and recorded throughout the whole test duration.
Figure 22: The CGHAZ-simulation thermal history and OSU SRC Test

Figure 23: The 3-pass weld thermal history and OSU SRC Test
Figure 24: Top view of The OSU SRC Test setup – Dogbone sample in serrated stainless steel hot grips with thermocouple and ceramic rods from the extensometer

3.6 CCT Diagram Development

The Gleeble® 3800 thermomechanical physical simulation and tester was used for the development of a continuous cooling transformation (CCT) diagram for the CGHAZ region of creep-resistant steels. Cylindrical samples were machined from Grade T12, T22, T23, and T24 materials as discussed in Section 3.2.3. Low-force jaws were
utilized in the Gleeble® in order to allow for thermal expansion of the sample on heating, therefore limiting induced stresses during the thermal cycle. A dilatometer was placed on the cylindrical sample in order to record the volume change on heating and on cooling in order to determine the start and finishing temperatures of the phase transformations that occur in these steels, as shown in Figure 25 and Figure 26. Samples were placed into smooth cylindrical copper grips and were heated at a rate of 100°C/second up to a peak temperature of 1350°C where they were held for 1 second. The samples were then free cooled back to room temperature. The cooling rate was determined by the free span between the copper grips where faster cooling rates, or shorter $t_{8/5}$ times, were achieved when the copper grips were closer together and slower cooling rates, or longer $t_{8/5}$ times, when the grips were further apart.

![Dilatometer Image](image)

**Figure 25: Dilatometer**
Figure 26: Gleeble® dilatometer setup, low-force jaws, smooth copper grips

An example of a resultant curve from a dilatometer measurement is shown in Figure 27 where the dilation is recorded against temperature. The image on the left shows the full dilation curve while the image on the right shows the region of the curve where the transformation start and finish temperatures are found. The slope change on cooling from the peak temperature indicates a phase transformation. The start and finishing phase transformation temperatures are found by using this slope change, which is associated with the change in volume of the sample.
Figure 27: CCT dilatometry curve example, determination of transformation start and finish temperatures \((T_{12}, t_{8/5} = 44.3 \text{ sec})\), dilation is recorded against temperature

3.7 Metallography

In samples that underwent failure, one half of the sample was cut longitudinally with an abrasive cut-off saw in order to view the microstructure while the other half of the failed sample was kept for fractography. Samples that needed to be observed in the scanning electron microscope (SEM) were mounted in electrically conductive bakelite while all other samples were mounted with non-conductive bakelite. All samples were ground with SiC grit pads up to 800 grit paper and then polished with diamond paste.
down to 3 µm and were immediately rinsed after each step with either ethanol or acetone and then ultrasonically cleaned and dried after each step. Water was not used to rinse the samples after each step as water seemed to increase the probability of pitting in the steels used for this research. Etching was performed by swabbing the samples with a cotton ball of 5% nital for all samples for around 15-25 seconds or until the microstructure was visible. Light optical microscopy was performed with an Olympus GX51. Scanning electron microscopy was performed with a FEI™ Quanta 200 SEM.

3.8 Vickers Hardness Measurements

Vickers Hardness measurements were made with a LECO LM-100AT microhardness indenter. For the cylindrical samples used for CCT diagram development, a 1 kg load was used as shown in Figure 28 where the hardness indents are aligned along the plane of the thermocouple. When hardness mapping was performed, a 100 gram load was used and indents had 100 µm spacing in between them.
3.9 Fractography

Fractographic analysis was performed on a few of the tested samples that failed in the FEI™ Quanta 200 SEM. One half of each failed sample was first coated with nail polish in order to protect the fracture surface during cutting. Each sample fracture surface was then cut from the larger portion of the dogbone sample so that the fracture surface could easily be mounted and put into the SEM. After cutting, the nail polish was ultrasonically cleaned from the fracture surface for about 45 minutes and was then it was rinsed with acetone and dried.
3.10 Reduction in Area

A binocular microscope was used to take a top view photo of one half of each failed sample. Image analysis was performed using Photoshop and ImageJ in order to determine the reduction in area of each tested sample.
CHAPTER 4: RESULTS AND DISCUSSION

4.1 The OSU SRC Test – Simulated CGHAZ, T24

In order to quantify the stress-relief cracking susceptibility, many variables were measured and/or calculated including the applied stress at room temperature, stress and elongation at the holding temperature, time to failure, stress and elongation at failure, total elongation for the duration of the test and reduction in area. The total elongation is the elongation experienced for the whole duration of the test while the elongation at failure only accounts for the elongation experienced at the testing temperature. Details regarding The OSU SRC test and sample preparation for simulated-CGHAZ samples were described in sections 3.5 and 3.2.1, respectively.

Grade T24 steel is delivered in the normalized and tempered condition. Tubing with an outer diameter (OD) of 44.5 mm and a wall thickness of 7 mm was evaluated in the study of the simulated-CGHAZ of Grade T24 steel. The value for 90% of the yield strength (0.9YS) was found to be 975 MPa for the simulated-CGHAZ of Grade T24 and a total of six samples were tested. Samples tested at 600 and 650°C survived the full 8 hour
hold and had to be pulled to failure, the samples tested at 675 and 700°C failed on holding at the test temperature and the sample tested at 725 and 750°C failed on heating.

Light optical microscopy (LOM) images as well as graphs of force and temperature versus time, stress and strain versus time, and stress versus strain are available for the simulated CGHAZ samples of Grade T24 in Appendix: A.1 The OSU SRC Test – Simulated CGHAZ, T24. SEM micrographs are available for the samples tested at 650°C and 700°C.

4.1.1 SRC testing of simulated CGHAZ in Grade T24 steel – 600°C

The CGHAZ sample tested at 600°C failed in a completely ductile manner with no signs of intergranular failure which is representative of SRC as shown in Figure 29 and Figure 30. There is apparent reduction in the cross-sectional area visible in Figure 29 and the decarburized layer formed during tube production is made visible by etching with 5% Nital. Figure 30 clearly shows elongation of the grains near the fracture surface from being pulled to failure after the 8 hours of holding at 600°C.

Figure 31 shows the stress and strain versus time to failure at 600°C. On heating, the applied stress decreases from 987 MPa at room temperature to 446 MPa at 600°C. This is due to generation of thermal expansion stress in the gauge section during heating under constant displacement. Notice that the strain is very low for the full duration of the 8 hour test and there is essentially no stress reduction. This shows that there was little or
no stress relief occurring during holding at a temperature of 600°C. The stress at failure, $(\sigma_{\text{failure}})$ was 815 MPa and the strain at failure $(\varepsilon_{\text{failure}})$ was 0.325.

Figure 29: Grade T24, longitudinal section, ductile failure, test temperature 600°C, 

$\sigma_{\text{failure}} = 815$ MPa, $\varepsilon_{\text{failure}} = 0.325$ (pulled to failure)
Figure 30: Grade T24, longitudinal section, elongated grains visible near fracture surface, test temperature 600°C, $\sigma_{\text{failure}} = 815$ MPa, $\varepsilon_{\text{failure}} = 0.325$ (pulled to failure)

Figure 31: Grade T24, stress and strain versus time, test temperature 600°C, $\sigma_{\text{failure}} = 815$ MPa, $\varepsilon_{\text{failure}} = 0.325$ (pulled to failure)
4.1.2 SRC testing of simulated CGHAZ in Grade T24 steel – 650°C

The simulated-CGHAZ sample tested at 650°C failed in a mostly brittle intergranular manner as shown in Figure 32, Figure 33 and Figure 34 even though it was pulled to failure after lasting the full 8 hours at temperature. Some intergranular cracking along with slight elongation of a few grains closest to the fracture surface is visible in Figure 33. Figure 34 and Figure 35 are SEM images. Figure 34 shows mainly intergranular failure with some ductility present and a few unidentified blocky particles which could be titanium carbide precipitates. Figure 35 shows ductile dimples more clearly along with a blocky particle.

Figure 36 shows the stress and strain versus time to failure at 650°C. Notice that the strain was very low for the full duration of the 8 hour test and there is a small reduction in the stress. This leads us to assume that embrittlement was occurring and some of the cracks were formed during holding which led to a slight decrease in the stress during holding. The assumption is supported by the low strain at failure (only 0.011). The stress at failure was 669 MPa.
Figure 32: Grade T24, longitudinal section, mostly brittle failure, test temperature 650°C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
Figure 33: Grade T24, longitudinal section, some intergranular cracking visible, slight elongation of some grains, test temperature 650°C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
Figure 34: Grade T24, SEM - Mainly intergranular failure, some ductility present, unidentified blocky particles, test temperature 650°C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
Figure 35: Grade T24, SEM – Ductile dimples, unidentified blocky particles, test temperature $650^\circ C$, $\sigma_{\text{failure}} = 669 \text{ MPa}$, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
4.1.3 SRC testing of simulated CGHAZ in Grade T24 steel – 700°C

The CGHAZ sample tested at 700°C failed during testing after being held for 11 minutes at temperature in a brittle intergranular manner as shown in Figure 37, Figure 38 and Figure 39. The SEM image of the fracture surface in this sample in Figure 39 does not show any ductile features as those found in the sample tested at 650°C. The unidentified particles, which are likely titanium carbide, are seen in the sample tested at 700°C much like in the sample tested at 650°C. There are no signs of ductile elongation.
in the test sample (Figure 37). Figure 38 shows evidence of brittle intergranular cracking in the HAZ.

Figure 40 shows the stress and strain versus time at 700°C. There was a large decrease in stress and a significant increase in strain during the 11 minute hold at 700°C until the sample failed. The short time to failure, the extremely low strain at failure (0.0007) and the fully intergranular fracture mode provide evidences that the failure mechanism was SRC. The stress at failure was 406 MPa.
Figure 37: Grade T24, longitudinal section, brittle failure, test temperature 700°C,

\[ \sigma_{\text{failure}} = 406 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.0007 \] (failed on holding after 11 min)
Figure 38: Grade T24, longitudinal section, intergranular cracking, test temperature 700°C, $\sigma_{\text{failure}} = 406$ MPa, $\varepsilon_{\text{failure}} = 0.0007$ (failed on holding after 11 min)
Figure 39: Grade T24, intergranular cracking, unidentified particles present, test temperature 700°C, $\sigma_{\text{failure}} = 406 \text{ MPa}$, $\varepsilon_{\text{failure}} = 0.0007$ (failed on holding after 11 min)
Figure 40: Grade T24, stress and strain versus time, test temperature 700°C, \( \sigma_{\text{failure}} = 406 \text{ MPa}, \varepsilon_{\text{failure}} = 0.0007 \) (failed on holding after 11 min)

4.1.4 SRC testing of simulated CGHAZ in Grade T24 steel – 750°C

The CGHAZ sample intended for testing at 750°C failed at 729°C on heating in a brittle intergranular manner as shown in Figure 41. Figure 42 shows the stress and strain versus time curves for this sample. The sample underwent embrittlement and failed by SRC during heating. The stress at failure was 361 MPa and the total strain was 0.035.
Figure 41: Grade T24, longitudinal section, brittle failure, test temperature 729°C,

\[ \sigma_{\text{failure}} = 361 \text{ MPa}, \varepsilon_{\text{failure}} = 0 \text{ (failed on heating)} \]
Figure 42: Grade T24, stress and strain versus time, test temperature 729°C, $\sigma_{\text{failure}} = 361$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating)

4.1.5 Summary of results - The OSU SRC Test, Simulated-CGHAZ T24

The results for all SRC tests performed on simulated-CGHAZ samples of Grade T24 steel are summarized in Table 7 and in Figure 43 and Figure 44. The applied tensile stress at room temperature is relatively consistent. The initial stress at holding temperature is significantly lower than the stress originally applied at room temperature due to thermal expansion in the gauge section during heating under displacement control.
The samples tested at 600 and 650°C did not fail during holding at test temperature and were pulled to failure as shown in Figure 43. The samples tested at 675 and 700°C failed during holding at test temperature. The samples with intended testing temperatures of 725 and 750°C failed on heating correspondingly at 725 and 729°C. The time to failure, stress and strain at failure, total strain and reduction in area decrease significantly at testing temperatures above 600°C as shown in Table 7, Figure 43, and Figure 44. The failure mode changes from ductile at 600°C to predominantly intergranular with ductile features at 650°C and to purely intergranular at higher testing temperatures.

These results show that the failure mechanism in simulated CGHAZ of Grade T24 steel for these particular testing conditions is stress relief cracking. The sample tested at 650°C did not fail for eight hours at a tensile stress of 414 MPa and had to be strained to failure. However, the low strain at failure and low reduction in area provide evidence that stress relaxation embrittlement had already occurred during the holding stage at 650°C. The on-heating failures at 725 and 729°C show that stress relief embrittlement may also occur during slow heating to high temperatures under high tensile stress and high restraint.

There is a trend of gradual reduction in the time to failure and strain at failure with increasing the testing temperature to 725°C. The total strain and reduction in area above 600°C and the stress at failure above 650°C remain almost constant. Consequently,
the time to failure and the strain at failure (defined in this study as the strain experienced at testing temperature) are more sensitive indicators of susceptibility to SRC.

The stress relief cracking in the tested material is potentially related to intragranular strengthening caused by re-precipitation of carbides that have been dissolved during the CGHAZ simulation and to simultaneous embrittlement along the prior austenite grain boundaries. Further high level metallurgical characterization work is needed to clarify the embrittlement mechanism in the tested material.
<table>
<thead>
<tr>
<th>Test T (°C)</th>
<th>Applied Stress at RT (MPa)</th>
<th>Stress at holding T (MPa)</th>
<th>Time to Failure (hrs)</th>
<th>Elongation at failure (%)</th>
<th>Total elongation (%)</th>
<th>RA (%)</th>
<th>Stress at failure (MPa)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>987</td>
<td>485</td>
<td>8, pulled</td>
<td>32.5</td>
<td>34.4</td>
<td>44</td>
<td>815</td>
<td>D</td>
</tr>
<tr>
<td>650</td>
<td>975</td>
<td>414</td>
<td>8, pulled</td>
<td>1.1</td>
<td>2.8</td>
<td>8</td>
<td>669</td>
<td>IG + D</td>
</tr>
<tr>
<td>675</td>
<td>988</td>
<td>416</td>
<td>3.54</td>
<td>0.7</td>
<td>2.8</td>
<td>7</td>
<td>390</td>
<td>IG</td>
</tr>
<tr>
<td>700</td>
<td>988</td>
<td>423</td>
<td>0.18</td>
<td>0.07</td>
<td>2.4</td>
<td>7</td>
<td>406</td>
<td>IG</td>
</tr>
<tr>
<td>725</td>
<td>989</td>
<td>N.A.</td>
<td>on heating at 725°C</td>
<td>N.A.</td>
<td>2.3</td>
<td>7</td>
<td>385</td>
<td>IG</td>
</tr>
<tr>
<td>750</td>
<td>994</td>
<td>N.A.</td>
<td>on heating at 729°C</td>
<td>N.A.</td>
<td>3.5</td>
<td>7</td>
<td>361</td>
<td>IG</td>
</tr>
</tbody>
</table>
Figure 43: Temperature versus time to failure at holding temperature for the simulated-CGHAZ in Grade T24 steel
Figure 44: Stress, elongation, and reduction in area at failure versus temperature for simulated-CGHAZ samples of Grade T24 steel

4.2 The OSU SRC Test – 3-pass welds

The stress-relief cracking susceptibility is quantified in a similar manner that was performed for the simulated-CGHAZ samples of T24 as described in section 4.1. Details regarding The OSU SRC test and sample preparation for 3-pass weld samples were described in sections 3.5 and 3.2.2, respectively.
Grades T12, T22, T23, and T24 steel were delivered in the normalized and tempered condition. Tubing dimensions of the materials evaluated in this study are shown in Table 8. Room temperature tensile testing was performed on each 3-pass weld material, as described in section 3.4, in order to determine the yield strength at room temperature. The OSU SRC test needs the values for 90% of the yield strength (0.9YS) for each Grade of steel, and these values are shown in Table 9. Grades T12 and T22 were lathed prior to welding in order to create a more uniform cross section between all the test samples while the weld root was kept intact, unaffected by the lathing process.

Graphs of force and temperature versus time, stress and strain versus time, and stress versus strain are available for the 3-pass weld samples of Grades T12, T22, T23, and T24 in Appendices A2 – A5 and a few of the samples have optical micrographs available.
Table 8: Material tubing dimensions, wall thickness before and after lathing

<table>
<thead>
<tr>
<th>Material</th>
<th>OD (mm)</th>
<th>Wall Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Before</td>
</tr>
<tr>
<td>T12</td>
<td>50.8</td>
<td>9.1</td>
</tr>
<tr>
<td>T22</td>
<td>50.0</td>
<td>12.5</td>
</tr>
<tr>
<td>T23</td>
<td>38.0</td>
<td>6.3</td>
</tr>
<tr>
<td>T24</td>
<td>44.5</td>
<td>7.1</td>
</tr>
</tbody>
</table>
Table 9: Room temperature tensile testing on 3-pass weld samples

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Strength (MPa)</th>
<th>0.9 of YS (MPa)</th>
<th>Ultimate Tensile Stress (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T12</td>
<td>617</td>
<td>555</td>
<td>838</td>
<td>19</td>
</tr>
<tr>
<td>*T22</td>
<td>770</td>
<td>693</td>
<td>1029</td>
<td>25</td>
</tr>
<tr>
<td>T23</td>
<td>741</td>
<td>667</td>
<td>1179</td>
<td>48</td>
</tr>
<tr>
<td>T24</td>
<td>818</td>
<td>736</td>
<td>1209</td>
<td>50</td>
</tr>
</tbody>
</table>

*Note: Grade T22 test is the only sample that did not break in the weld during testing, instead it failed in the base material.

In this study of 3-pass welds, we see several types of failure modes including ductile failure, brittle failure on holding, cracking on holding, cracking on heating, and failure on heating. Examples are given for each failure mode. For ductile failure, an example is shown in Figure 45 and Figure 46 for Grade T24 tested at 600°C and the corresponding stress and strain versus time graph is shown in Figure 47. In Figure 46, the grains appear to be elongated in a ductile manner. Some samples failed in a brittle...
manner on holding such as Grade T23 tested at 650°C where longitudinal sections are shown in Figure 48 and Figure 49 while an example stress and strain versus time graph is shown in Figure 50. Some samples cracked and later failed during holding and examples are shown in Figure 51 and Figure 52 for Grade T24 tested at 650°C and the corresponding stress and strain versus time graph is shown in Figure 53. Examples of a sample that cracked on heating at a temperature of 707°C are shown in Figure 54 and Figure 55 for Grade T24 tested at 750°C and the corresponding stress and strain versus time graph is shown in Figure 56. Figure 57 and Figure 58 show longitudinal sections of the Grade T23 3-pass weld sample that failed on heating at 742°C when being heated to 750°C while Figure 59 shows the corresponding stress and strain versus time graph.
Figure 45: T24 3-pass weld, longitudinal section, test temperature 600°C, $\sigma_{\text{failure}} = 819$ MPa, $\varepsilon_{\text{failure}} = 0.27$ (pulled to failure after 12 hours holding)
Figure 46: T24 3-pass weld, longitudinal section, test temperature 600°C, \( \sigma_{\text{failure}} = 819 \text{ MPa}, \varepsilon_{\text{failure}} = 0.27 \) (pulled to failure after 12 hours holding)
Figure 47: T24 3-pass weld, stress and strain versus time, test temperature 600°C,

\[ \sigma_{\text{failure}} = 819 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.27 \] (pulled to failure after 12 hours holding)
Figure 48: Grade T23 3-pass weld, longitudinal section, test temperature 650°C,

\[ \sigma_{\text{failure}} = 191 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.047 \] (failed on holding after 1.69 hours)
Figure 49: Grade T23 3-pass weld, longitudinal section, test temperature 650°C,

\[ \sigma_{\text{failure}} = 191 \text{ MPa}, \quad \varepsilon_{\text{failure}} = 0.047 \text{ (failed on holding after 1.69 hours)} \]
Figure 50: Grade T23 3-pass weld, stress and strain versus time, test temperature 650°C, $\sigma_{\text{failure}} = 191$ MPa, $\varepsilon_{\text{failure}} = 0.047$ (failed on holding after 1.69 hours)
Figure 51: Grade T24 3-pass weld, longitudinal section, test temperature 650°C, 

\[ \sigma_{\text{failure}} = 133 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.087 \] (cracked on holding after 5.1 hours at 650°C, failed on holding after 6.3 hours)
Figure 52: Grade T24 3-pass weld, longitudinal section, test temperature 650°C, 

$\sigma_{\text{failure}} = 133$ MPa, $\varepsilon_{\text{failure}} = 0.087$ (cracked on holding after 5.1 hours at 650°C, failed on holding after 6.3 hours)
Figure 53: Grade T24 3-pass weld, stress and strain versus time, test temperature

650°C, $\sigma_{\text{failure}} = 133$ MPa, $\varepsilon_{\text{failure}} = 0.087$ (failed on holding after 6.3 hours)
Figure 54: Grade T24 3-pass weld, longitudinal section, test temperature 750°C, 

\( \sigma_{\text{failure}} = 132 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.089 \) (cracked on heating at 707°C, pulled to failure after 8 hours)
Figure 55: Grade T24 3-pass weld, longitudinal section, test temperature 750°C, 

$\sigma_{\text{failure}} = 132$ MPa, $\varepsilon_{\text{failure}} = 0.089$ (cracked on heating at 707°C, pulled to failure after 8 hours)
Figure 56: Grade T24 3-pass weld, stress and strain versus time, test temperature 750°C, $\sigma_{\text{failure}} = 132$ MPa, $\varepsilon_{\text{failure}} = 0.089$ (cracked on heating at 707°C, pulled to failure after 8 hours)
Figure 57: Grade T23 3-pass weld, longitudinal section, test temperature $742^\circ$C,

\[ \sigma_{\text{failure}} = 150 \text{ MPa}, \varepsilon_{\text{failure}} = 0 \text{ (failed on heating at } 742^\circ\text{C)} \]
Figure 58: Grade T23 3-pass weld, longitudinal section, test temperature 742°C,

\[ \sigma_{\text{failure}} = 150 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0 \] (failed on heating at 742°C)
Figure 59: Grade T23 3-pass weld, stress and strain versus time, test temperature 742°C, $\sigma_{\text{failure}} = 150$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at 742°C)

3.2.1 Grade T24 steel – SRC testing of 3-pass welds

A total of seven samples of Grade T24 steel 3-pass welds were tested as shown in Table 10. The targeted room temperature stress was 736 MPa, although, overshooting lead to an average of 778 MPa as the initial applied stress and four test samples were given this stress at room temperature. Three samples were tested at higher initial stresses around 1062 MPa at room temperature and this value is above the yield strength for T24.
and so the sample is said to be overloaded. This overloading effect is best visualized in Figure 61 as with overloading, there seems to be little to no dependence of the testing temperatures of 600, 650, and 700°C (failed on heating at 679°C) on the stress, percent elongation, or percent reduction in area of the tested samples. Overloading results in very low values for the percent elongation and reduction in area at cracking/failure. Figure 60 shows the temperature versus time to cracking (time to failure if no cracking) and it is apparent that overloading leads to shorter times to failure and thus greater susceptibility to cracking/failure, but the mechanism of failure may be due to creep rupture because of the high stresses experienced by the samples. The stress, elongation, and reduction in area values are much higher for the sample tested at 600°C than for samples tested at higher temperatures as shown in Figure 61 and the 600°C test sample had to be pulled to failure after holding at temperature for 12 hours. Based on this data, Grade T24 was determined to be not susceptible to stress-relief cracking at or below 600°C and susceptible to stress-relief cracking at temperatures of 650°C and above.
Table 10: OSU SRC Test Results – T24 (3-pass weld)

<table>
<thead>
<tr>
<th>°C</th>
<th>Applied stress at RT (MPa)</th>
<th>Stress at holding (MPa)</th>
<th>Time to cracking</th>
<th>Time to failure</th>
<th>Elongation at cracking, at holding T (%)</th>
<th>Elongation at failure, at holding T (%)</th>
<th>Total Elong. (%)</th>
<th>Reduction in Area (%)</th>
<th>Stress at cracking (MPa)</th>
<th>Stress at Failure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>1061</td>
<td>616</td>
<td>3.55 hrs at 600°C</td>
<td>8 hrs, Pulled</td>
<td>0.16</td>
<td>5.6</td>
<td>7.5</td>
<td>5</td>
<td>617</td>
<td>304</td>
</tr>
<tr>
<td>650</td>
<td>1062</td>
<td>602</td>
<td>0.32 hrs at 650°C</td>
<td>1.35 hrs at 650°C</td>
<td>0.19</td>
<td>7.9</td>
<td>10.6</td>
<td>7</td>
<td>577</td>
<td>214</td>
</tr>
<tr>
<td>700</td>
<td>1062</td>
<td>N.A.</td>
<td>N.A.</td>
<td>On heating at 679°C</td>
<td>N.A.</td>
<td>N.A.</td>
<td>2.7</td>
<td>6</td>
<td>N.A.</td>
<td>561</td>
</tr>
<tr>
<td>600</td>
<td>779</td>
<td>414</td>
<td>N.A.</td>
<td>12 hrs, Pulled</td>
<td>N.A.</td>
<td>27</td>
<td>28</td>
<td>47</td>
<td>N.A.</td>
<td>819</td>
</tr>
<tr>
<td>650</td>
<td>774</td>
<td>369</td>
<td>5.1 hrs at 600°C</td>
<td>6.3 hrs at 650°C</td>
<td>0.3</td>
<td>8.7</td>
<td>9.5</td>
<td>4</td>
<td>393</td>
<td>133</td>
</tr>
<tr>
<td>700</td>
<td>781</td>
<td>341</td>
<td>0.58 hrs at 700°C</td>
<td>3.9 hrs at 700°C</td>
<td>0.4</td>
<td>6.5</td>
<td>7.6</td>
<td>5</td>
<td>340</td>
<td>152</td>
</tr>
<tr>
<td>750</td>
<td>779</td>
<td>289</td>
<td>On heating at 707°C</td>
<td>8 hrs, Pulled</td>
<td>0</td>
<td>8.9</td>
<td>11.4</td>
<td>7</td>
<td>344</td>
<td>132</td>
</tr>
</tbody>
</table>
Figure 60: Temperature versus time to cracking (time to failure if no time to cracking) at holding temperature for Grade T24 steel at both higher (1062 MPa) and lower (778 MPa) initial stresses
Figure 61: Stress, elongation, and reduction in area cracking (at failure if no cracking) versus temperature for a 3-pass weld in Grade T24 steel at both higher (1062 MPa) and lower (778 MPa) initial stresses
3.2.2 Grade T23 steel – SRC testing of 3-pass welds

A total of seven samples of Grade T23 steel 3-pass welds were tested as shown in Table 11. The targeted room temperature stress was 667 MPa, although, overshooting lead to 712 MPa as the average initial applied stress and all samples were given this stress at room temperature. In order to determine the reproducibility of The OSU SRC Test, three Grade T23 steel samples were tested at 650°C and two were tested at 700°C. All of the samples of Grade T23 that were retested/repeated as well as the sample tested at 625°C came from a different tube and thus a different weld. This is important to note as the results for these samples are significantly different than the results obtained for the Grade T23 samples machined from the first tube. The 3-pass weld sample intended for testing at 750°C failed at 742°C on heating. The 3-pass weld sample tested at 625°C failed in a ductile manner based on the 33 percent reduction in area and high stress at failure of 670 MPa. Based on these results, Grade T23 is determined not to be susceptible to stress-relief cracking at temperatures of 625°C and below. Only one of the three samples tested at 650°C lasted for the full duration of the test while two of the samples failed before the end of the test, therefore it was concluded that Grade T23 is susceptible to stress-relief cracking at temperatures of 650°C and above.
Table 11: OSU SRC Test Results – T23 (3-pass weld)

<table>
<thead>
<tr>
<th>°C</th>
<th>Applied stress at RT (MPa)</th>
<th>Stress at holding (MPa)</th>
<th>Time to cracking</th>
<th>Time to failure</th>
<th>Elongation at cracking, at holding T (%)</th>
<th>Elongation at failure, at holding T (%)</th>
<th>Total Elong. (%)</th>
<th>Reduction in Area (%)</th>
<th>Stress at cracking (MPa)</th>
<th>Stress at failure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>*625</td>
<td>710</td>
<td>309</td>
<td>N.A.</td>
<td>8 hrs, Pulled</td>
<td>N.A.</td>
<td>1</td>
<td>2.1</td>
<td>N.A.</td>
<td>33</td>
<td>N.A.</td>
</tr>
<tr>
<td>650</td>
<td>707</td>
<td>280</td>
<td>N.A.</td>
<td>12 hrs, Pulled</td>
<td>N.A.</td>
<td>2.0</td>
<td>3.4</td>
<td>13</td>
<td>N.A.</td>
<td>540</td>
</tr>
<tr>
<td>*650 (repeat)</td>
<td>711</td>
<td>339</td>
<td>N.A.</td>
<td>1.69 hrs at 650°C</td>
<td>N.A.</td>
<td>4.7</td>
<td>5.5</td>
<td>9</td>
<td>N.A.</td>
<td>191</td>
</tr>
<tr>
<td>*650 (repeat 2)</td>
<td>713</td>
<td>350</td>
<td>N.A.</td>
<td>0.91 hrs at 650°C</td>
<td>N.A.</td>
<td>1</td>
<td>1.4</td>
<td>7</td>
<td>N.A.</td>
<td>334</td>
</tr>
<tr>
<td>700</td>
<td>714</td>
<td>300</td>
<td>3.8 hrs at 700°C</td>
<td>6.9 hrs at 700°C</td>
<td>0.7</td>
<td>6.8</td>
<td>8.4</td>
<td>8</td>
<td>262</td>
<td>87</td>
</tr>
<tr>
<td>*700 (repeat)</td>
<td>715</td>
<td>316</td>
<td>N.A.</td>
<td>7 min at 700°C</td>
<td>N.A.</td>
<td>2.9</td>
<td>4.2</td>
<td>8</td>
<td>N.A.</td>
<td>192</td>
</tr>
<tr>
<td>750</td>
<td>715</td>
<td>N.A.</td>
<td>N.A.</td>
<td>On heating at 742°C</td>
<td>N.A.</td>
<td>N.A.</td>
<td>7</td>
<td>4</td>
<td>N.A.</td>
<td>150</td>
</tr>
</tbody>
</table>

* Note: These samples are named “retested” samples and these are plotted separately
Figure 62: Temperature versus time to cracking (time to failure if no time to cracking) at holding temperature for Grade T23 steel, the sample at 625°C was pulled to failure after 8 hours and one sample at 650°C was pulled to failure after 12 hours.
Figure 63: Stress, elongation, and reduction in area at cracking (or at failure if no cracking) versus temperature for a 3-pass weld in Grade T23 steel, initial applied stress was 712 MPa
Figure 64: (Retested samples) – Stress, elongation, and reduction in area at cracking (or at failure if no cracking) versus temperature for a 3-pass weld in Grade T23 steel, initial applied stress was 712 MPa
3.2.3 Grade T22 steel – SRC testing of 3-pass welds

A total of three 3-pass weld samples of Grade T22 steel were tested, one at each temperature of 600, 650 and 700°C. The targeted room temperature stress was 693 MPa, although, overshooting lead to an average initial applied stress of 728 MPa. Figure 66 shows the stress and strain versus time for the sample tested at 600°C that was pulled to failure after a 12-hour hold at temperature. This leads us to assume that embrittlement was occurring and some cracks were formed during holding at 600°C and this leads to the decrease in stress during holding. While the sample tested at 600°C has a significantly greater reduction in area and thus greater ductility than the samples tested at 650 and 700°C and lasted for the full duration of the test, it may still be susceptible to stress-relief cracking due to the large decrease in the stress while at holding temperature.
Table 12: OSU SRC Test Results – T22 (3-pass weld)

<table>
<thead>
<tr>
<th>°C</th>
<th>Applied stress at RT (MPa)</th>
<th>Stress at holding (MPa)</th>
<th>Time to cracking</th>
<th>Time to failure</th>
<th>Elongation at cracking, at holding T (%)</th>
<th>Elongation at failure, at holding T (%)</th>
<th>Total Elong. (%)</th>
<th>Reduction in Area (%)</th>
<th>Stress at cracking (MPa)</th>
<th>Stress at failure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>729</td>
<td>330</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>4.3</td>
<td>5.5</td>
<td>47</td>
<td>N.A.</td>
<td>572</td>
</tr>
<tr>
<td>650</td>
<td>723</td>
<td>319</td>
<td>2.4 hrs</td>
<td>12 hrs</td>
<td>5.76 hrs</td>
<td>1.57</td>
<td>20.9</td>
<td>22.7</td>
<td>6</td>
<td>255</td>
</tr>
<tr>
<td>700</td>
<td>732</td>
<td>266</td>
<td>On heating</td>
<td>40 min</td>
<td>0</td>
<td>13.8</td>
<td>15.7</td>
<td>6</td>
<td>310</td>
<td>84</td>
</tr>
</tbody>
</table>
Figure 65: Temperature versus time to cracking (time to failure if no time to cracking) at holding temperature for Grade T22 steel
Figure 66: Stress and strain versus time, test temperature 600°C, $\sigma_{\text{failure}} = 572$ MPa, $\varepsilon_{\text{failure}} = 0.043$ (pulled to failure)
3.2.4 Grade T12 steel – SRC testing of 3-pass welds

The targeted room temperature stress for Grade T12 steel 3-pass weld samples was 555 MPa. A total of three samples were tested, one at each temperature of 650, 700 and 750°C. As shown in Figure 69, the low stress, elongation and reduction in area values may indicate that the samples may have been overloaded during testing as these values are not very dependent on the testing temperature. This could also indicate that Grade T12 is susceptible to stress-relief cracking at temperatures of 650°C and above.
Table 13: OSU SRC Test Results – T12 (3-pass weld)

<table>
<thead>
<tr>
<th>°C</th>
<th>Applied stress at RT (MPa)</th>
<th>Stress at holding (MPa)</th>
<th>Time to cracking</th>
<th>Time to failure</th>
<th>Elongation at cracking, at holding T (%)</th>
<th>Elongation at failure, at holding T (%)</th>
<th>Total Elong. (%)</th>
<th>Reduction in Area (%)</th>
<th>Stress at cracking (MPa)</th>
<th>Stress at failure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>549</td>
<td>212</td>
<td>N.A.</td>
<td>12 hrs, Pulled</td>
<td>N.A.</td>
<td>19.3</td>
<td>21</td>
<td>15</td>
<td>N.A.</td>
<td>122</td>
</tr>
<tr>
<td>700</td>
<td>559</td>
<td>181</td>
<td>1.77 hrs</td>
<td>8 hrs, Pulled</td>
<td>1.2</td>
<td>29</td>
<td>30</td>
<td>3</td>
<td>150</td>
<td>78</td>
</tr>
<tr>
<td>750</td>
<td>559</td>
<td>152</td>
<td>On heating at 739°C</td>
<td>8 hrs, Pulled</td>
<td>0</td>
<td>29.2</td>
<td>33</td>
<td>6</td>
<td>175</td>
<td>83</td>
</tr>
</tbody>
</table>
Figure 68: Temperature versus time to cracking (time to failure if no time to cracking) at holding temperature for Grade T12 steel
Figure 69: Stress, elongation, and reduction in area at cracking (at failure if no cracking) versus temperature for a 3-pass weld in Grade T12 steel, targeted initial applied stress 555 MPa

3.2.5 Summary of The OSU SRC Test 3-pass weld

Based on Figure 70, which shows the temperature versus time to cracking/failure, the order of stress-relief cracking susceptibility from most resistant to least resistant is: Grade T23, T12, T24, T23 (retest) and then T22. In Figure 71, T23 sustains the highest stress during tempering, followed by T24, T23 (retest), and T22. The lowest stress and linear dependence in T12 can be related to its low room temperature yield tensile strength and potential yielding (exceeding the yield strength) on heating. As shown in Figure 72,
Grade T23 and T12 seem to perform better in terms of sustained strain (elongation) before cracking than Grade T24 and T22.

Figure 73 shows the temperature versus time to cracking/failure graph for Grade T24 tested at both higher and lower initial stresses. The yield stress values for these 3-pass welds are shown in Table 9. There seems to be some effect of overloading above the room temperature yield strength. Looking at the stress at cracking/failure versus temperature graph in Figure 74, Grade T24 (1062 MPa – overloaded) and T12 stress values do not change much with temperature. Instead, these stress values show straight line behavior and this seems to be indicative of significant overloading above the room temperature yield strength and potential yielding on heating and on holding at PWHT temperature. The overloaded samples in Grade T24 show higher stress at cracking (correspondingly at 650°C and 675°C for T24) compared to the lower load samples. This behavior may be related to a potential precipitation strengthening reaction occurring under combination of high stress and plastic strain acting at high temperature. High level metallurgical characterization is needed to clarify the nature of this phenomenon.

The SRC susceptibility in the tested welds was evaluated based on the maximum PWHT temperature sustained without cracking/failure, the time to cracking/failure, then on the stress, elongation, and reduction in area at failure. Grade T23 and T24 steels seem to have a similar resistance to SRC that is higher than in Grade T22 welds. When looking at the time-to-failure and the strain at failure, the welds in Grade T12 performed better than or equal to the Grade T23 and T24 welds, but failed at significantly lower stress.
Figure 70: Temperature versus time to cracking (TTC), or time to failure if no cracking (TTF), for T12, T22, T23, and T24
Figure 71: Stress at cracking, or at failure if no cracking, for T12, T22, T23, and T24
Figure 72: Elongation at cracking, or at failure if no cracking, for T12, T22, T23, and T24
Figure 73: Temperature versus time to cracking (TTC), or time to failure if no cracking (TTF), for T24 (1062 MPa), and T24 (778 MPa)
Figure 74: Stress at cracking, or at failure if no cracking, for Grade T12, T24 (1062 MPa), and T24 (778 MPa)
4.3 Base metal CCT Diagram Development

In order to develop the base material continuous cooling transformation (CCT) diagram, Grades T12, T22, T23, and T24 were prepared as shown in section 3.2.3 and the procedure is detailed in section 3.6. The phase transformation start and finish temperatures were found for samples of each material cooled at rates in a range from 2 - 50 seconds based on free spans between the copper grips anywhere from 10 mm to 70 mm. The corresponding Vicker’s hardness value (an average of 10 indents made at 1 kg load on the plane where the thermocouple was placed, transverse to the longitudinal axis of the sample) was also found.

4.3.1 T24 - CCT Diagram

For Grade T24, the average Vickers hardness (HV, 1 kg load) range spans from 384 at the fastest cooling rate to 351 HV at the slowest cooling rate. As the cooling rate decreases (slower cooling), both the transformation start and finish temperatures increase because more time is allowed for diffusion to occur.
Table 14: Base metal T24 $t_{8/5}$ values and corresponding transformation temperatures using Gleeble®

<table>
<thead>
<tr>
<th>Free Span (mm)</th>
<th>$T_{\text{peak}}$ (°C)</th>
<th>$t_{8/5}$ (seconds)</th>
<th>Start (°C)</th>
<th>Finish (°C)</th>
<th>Average (of 10)</th>
<th>Stdev</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1353</td>
<td>2.5</td>
<td>511</td>
<td>359</td>
<td>384</td>
<td>9</td>
<td>401</td>
<td>370</td>
</tr>
<tr>
<td>15</td>
<td>1352</td>
<td>4.4</td>
<td>506</td>
<td>364</td>
<td>381</td>
<td>3</td>
<td>384</td>
<td>373</td>
</tr>
<tr>
<td>20</td>
<td>1352</td>
<td>6.2</td>
<td>505</td>
<td>349</td>
<td>379</td>
<td>8</td>
<td>392</td>
<td>369</td>
</tr>
<tr>
<td>25</td>
<td>1352</td>
<td>8.5</td>
<td>519</td>
<td>381</td>
<td>383</td>
<td>5</td>
<td>391</td>
<td>376</td>
</tr>
<tr>
<td>30</td>
<td>1353</td>
<td>11.9</td>
<td>521</td>
<td>385</td>
<td>373</td>
<td>8</td>
<td>381</td>
<td>358</td>
</tr>
<tr>
<td>35</td>
<td>1353</td>
<td>14.1</td>
<td>526</td>
<td>383</td>
<td>378</td>
<td>7</td>
<td>392</td>
<td>367</td>
</tr>
<tr>
<td>40</td>
<td>1354</td>
<td>18.2</td>
<td>527</td>
<td>381</td>
<td>365</td>
<td>5</td>
<td>373</td>
<td>358</td>
</tr>
<tr>
<td>45</td>
<td>1355</td>
<td>20.5</td>
<td>533</td>
<td>381</td>
<td>361</td>
<td>9</td>
<td>375</td>
<td>348</td>
</tr>
<tr>
<td>50</td>
<td>1356</td>
<td>25.4</td>
<td>536</td>
<td>372</td>
<td>355</td>
<td>10</td>
<td>378</td>
<td>347</td>
</tr>
<tr>
<td>60</td>
<td>1358</td>
<td>31.0</td>
<td>547</td>
<td>382</td>
<td>355</td>
<td>10</td>
<td>378</td>
<td>342</td>
</tr>
<tr>
<td>70</td>
<td>1359</td>
<td>39.9</td>
<td>551</td>
<td>382</td>
<td>351</td>
<td>7</td>
<td>366</td>
<td>342</td>
</tr>
</tbody>
</table>
Figure 75: Base metal Grade T24 cooling curves and $t_{8/5}$ values
Figure 76: 5% Nital Etch of Grade T24, $t_{8/5} = 2.5$ seconds, $HV_{avg} = 384$

Figure 77: 5% Nital Etch of Grade T24, $t_{8/5} = 14.1$ seconds, $HV_{avg} = 378$
Figure 78: 5% Nital Etch of Grade T24, $t_{8/5} = 39.9$ seconds, $HV_{avg} = 351$
4.3.2 T23 - CCT Diagram

For Grade T23, the average Vickers hardness (HV, 1 kg load) range spans from 362 to 341 HV. As the cooling rate decreases (slower cooling), both the transformation start and finish temperatures increase because more time is allowed for diffusion to occur.
Table 15: Base metal T23 $t_{8/5}$ values and corresponding transformation temperatures using Gleeble

<table>
<thead>
<tr>
<th>Free Span (mm)</th>
<th>$T_{\text{peak}}$ (°C)</th>
<th>$t_{8/5}$ (seconds)</th>
<th>Transformation start and finish (°C)</th>
<th>Vickers Hardness (HV) 1 kg load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Start (°C)</td>
<td>Finish (°C)</td>
</tr>
<tr>
<td>10</td>
<td>1351</td>
<td>2.1</td>
<td>542</td>
<td>386</td>
</tr>
<tr>
<td>15</td>
<td>1353</td>
<td>4.1</td>
<td>571</td>
<td>384</td>
</tr>
<tr>
<td>20</td>
<td>1351</td>
<td>5.9</td>
<td>569</td>
<td>384</td>
</tr>
<tr>
<td>25</td>
<td>1352</td>
<td>7.8</td>
<td>575</td>
<td>389</td>
</tr>
<tr>
<td>30</td>
<td>1354</td>
<td>11.0</td>
<td>578</td>
<td>386</td>
</tr>
<tr>
<td>35</td>
<td>1353</td>
<td>14.4</td>
<td>578</td>
<td>385</td>
</tr>
<tr>
<td>40</td>
<td>1354</td>
<td>17.8</td>
<td>573</td>
<td>378</td>
</tr>
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<td>45</td>
<td>1355</td>
<td>21.6</td>
<td>577</td>
<td>397</td>
</tr>
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<td>50</td>
<td>1354</td>
<td>33.7</td>
<td>580</td>
<td>397</td>
</tr>
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<td>60</td>
<td>1356</td>
<td>42.2</td>
<td>582</td>
<td>400</td>
</tr>
<tr>
<td>70</td>
<td>1375</td>
<td>52.2</td>
<td>585</td>
<td>404</td>
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</tbody>
</table>
Figure 80: Base metal Grade T23 cooling curves and $t_{85}$ values
Figure 81: 5% Nital Etch of Grade T23, $t_{8/5} = 2.1$ seconds, $HV_{avg} = 360$

Figure 82: 5% Nital Etch of Grade T23, $t_{8/5} = 14.4$ seconds, $HV_{avg} = 356
Figure 83: 5% Nital Etch of Grade T23, \(t_{8/5} = 52.2\) seconds, \(HV_{\text{avg}} = 341\)
4.3.3 T22 - CCT Diagram

For Grade T22, the average Vickers hardness (HV, 1 kg load) range spans from 369 to 315 HV. As the cooling rate decreases (slower cooling), both the transformation start and finish temperatures increase because more time is allowed for diffusion to occur.
Table 16: Base metal Grade T22 t_{8/5} values and corresponding transformation temperatures using Gleeble®

<table>
<thead>
<tr>
<th>Free Span (mm)</th>
<th>T_{peak} (°C)</th>
<th>t_{8/5} (seconds)</th>
<th>Transformation start and finish (°C)</th>
<th>Transformation start and finish (°C)</th>
<th>Vickers Hardness (HV) 1 kg load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Start (°C)</td>
<td>Finish (°C)</td>
<td>Start (°C)</td>
</tr>
<tr>
<td>10</td>
<td>1353</td>
<td>2.6</td>
<td>*</td>
<td>*</td>
<td>483</td>
</tr>
<tr>
<td>15</td>
<td>1352</td>
<td>4.2</td>
<td>*</td>
<td>*</td>
<td>496</td>
</tr>
<tr>
<td>20</td>
<td>1354</td>
<td>5.6</td>
<td>*</td>
<td>*</td>
<td>509</td>
</tr>
<tr>
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<td>30</td>
<td>1353</td>
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<td>*</td>
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<td>32.5</td>
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<td>13.3</td>
<td>*</td>
<td>*</td>
<td>523</td>
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<td>1355</td>
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<td>1356</td>
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<td>*</td>
<td>*</td>
<td>537</td>
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<td>60</td>
<td>1358</td>
<td>42.6</td>
<td>*</td>
<td>*</td>
<td>549</td>
</tr>
<tr>
<td>70</td>
<td>1359</td>
<td>51.8</td>
<td>618</td>
<td>*</td>
<td>538</td>
</tr>
</tbody>
</table>

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Figure 85: Base metal Grade T22 cooling curves and $t_{85}$ values
Figure 86: 5% Nital Etch of Grade T22, $t_{8/5} = 2.6$ seconds, $HV_{avg} = 369$

Figure 87: 5% Nital Etch of Grade T22: $t_{8/5} = 13.3$ seconds, $HV_{avg} = 332$
Figure 88: 5% Nital Etch of Grade T22, $t_{85} = 42.6$ seconds, $HV_{avg} = 305$
4.3.4  T12 - CCT Diagram

For Grade T12, the average Vickers hardness (HV, 1 kg load) range spans from 344 to 226 HV. As the cooling rate decreases (slower cooling), both the transformation start and finish temperatures increase because more time is allowed for diffusion to occur.
Table 17: Base metal Grade T12 $t_{8/5}$ values and corresponding transformation temperatures using Gleeble®

<table>
<thead>
<tr>
<th>Free Span (mm)</th>
<th>$T_{\text{peak}}$ (°C)</th>
<th>$t_{8/5}$ (seconds)</th>
<th>Transformation start and finish (°C)</th>
<th>Vickers Hardness (HV) 1 kg load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Start (°C)</td>
<td>Finish (°C)</td>
</tr>
<tr>
<td>10</td>
<td>1352</td>
<td>2.5</td>
<td>569</td>
<td>343</td>
</tr>
<tr>
<td>15</td>
<td>1353</td>
<td>4.4</td>
<td>575</td>
<td>343</td>
</tr>
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<td>20</td>
<td>1354</td>
<td>6.6</td>
<td>599</td>
<td>360</td>
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<td>25</td>
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<td>9.3</td>
<td>611</td>
<td>382</td>
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<td>12.9</td>
<td>608</td>
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<td>27.2</td>
<td>620</td>
<td>448</td>
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<td>60</td>
<td>1359</td>
<td>36.1</td>
<td>627</td>
<td>466</td>
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<td>70</td>
<td>1363</td>
<td>44.3</td>
<td>627</td>
<td>459</td>
</tr>
</tbody>
</table>
Figure 90: Base metal Grade T12 cooling curves and $t_{85}$ values
Figure 91: 5% Nital Etch of Grade T12, \( t_{8/5} = 2.5 \) seconds, \( HV_{avg} = 344 \)

Figure 92: 5% Nital Etch of Grade T12: \( t_{8/5} = 12.9 \) seconds, \( HV_{avg} = 252 \)
Figure 93: 5% Nital Etch of Grade T12, $t_{s/g} = 44.3$ seconds, $H_{V_{avg}} = 226$
4.3.5 Summary of the Base Metal CCT Diagram Development

The phase transformation start and finish temperatures for Grades T12, T22, T23, and T24 are shown in Figure 95. As the cooling rate decreases (slower cooling and larger $t_{8/5}$ values), both the transformation start and finish temperatures increase because more time is allowed for diffusion to occur. The material with the lowest amount of alloying additions, Grade T12, has the largest increase in the phase transformation start and finish temperatures while the material with the most alloying additions and higher carbon...
content, Grade T24, has the least amount of increase in the phase transformation start and finish temperatures. Figure 96 shows Vicker’s hardness values as a function of $t_{8/5}$ (cooling rate) where Grade T12 hardness values are the most dependent on the cooling rate, followed by T22, T23, then Grade T24 hardness values are the least dependent on the cooling rate.

![Figure 95: Transformation start and finish temperatures (°C) versus $t_{8/5}$ values for Grades T12, T22, T23, and T24](image-1)

Figure 95: Transformation start and finish temperatures (°C) versus $t_{8/5}$ values for Grades T12, T22, T23, and T24
Figure 96: Hardness (1 kg load, HV) versus $t_{8/5}$ (sec) for Grades T12, T22, T23, and T24
CHAPTER 5: CONCLUSIONS

5.1 The OSU Stress Relief Cracking Test

1. A new stress relief cracking (SRC) test procedure has been developed at OSU that replicates post weld heat treatment (PWHT) in welds of highly restrained components loaded with high residual stresses.

2. The time to failure, stress and strain at failure, and reduction in area are quantified in this testing procedure and can be utilized as indicators for ranking susceptibility to SRC. The time to failure and strain at failure appear to be the most sensitive indicators of SRC susceptibility in the tested material.
5.2 Stress Relief Cracking Susceptibility in Simulated CGHAZ of Grade T24 steel

1. Simulated coarse grained heat affected zone (CGHAZ) in Grade T24 steel is not susceptible to SRC during PWHT at 600°C under high restraint, even when preloaded with yield level tensile stress at room temperature.

2. Stress relief embrittlement occurs in simulated CGHAZ of Grade T24 steel during PWHT at 650°C and higher temperatures under high restraint and high stress level. The kinetics of embrittlement accelerates significantly with increasing the PWHT temperature. This is evidenced by the decreasing time to failure and strain at failure during PWHT at 650, 675 and 700°C, and by complete sample failures during heating to 725 and 729°C.
5.3 Stress Relief Cracking Susceptibility in 3-pass Welds of Grade T12, T22, T23, and T24 Steels

1. The SRC susceptibility in the tested welds was evaluated based on the maximum PWHT temperature sustained without failure, on the time-to-failure, and on the stress, elongation, and reduction in area at failure. Overall, the welds in Grade T23 and T24 steel had similar resistance to SRC that was higher than in the T22 welds. In terms of time-to-failure and strain at failure, the welds in Grade T12 performed better than or equal to the T23 and T24 welds, but failed at significantly lower stress.

2. Partial cracking by stress relief mechanism was experienced in particular welds of all tested steels. The cracks were predominantly intergranular and nucleated in the cap pass of the test welds. In most cases, these cracks formed during holding at the PWHT temperature and caused complete failure later in the process of holding.

3. The fracture morphology in all welds that did not fail during simulated PWHT and were pulled to failure was predominantly ductile with evidences of intergranular crack nucleation. The fracture morphology in welds failed during PWHT was predominantly intergranular with ductile features in welds tested at higher temperatures.
4. Highly restrained welds in Grade T22, T23, and T24 steels that are loaded with high level residual stresses, such as in water wall panels of ultra-supercritical fossil power plants, may be potentially susceptible to stress relief cracking during PWHT in the temperature range above 600°C. Further investigations are needed to determine safe PWHT temperatures in such welds.
5.4 Phase Transformation Behavior in Simulated CGHAZ of Grade T12, T22, T23, and T24 Steels

1. Continuous cooling transformation (CCT) diagrams have been developed for simulated CGHAZ in Grade T12, T22, T23, and T24 steels for the range of cooling times between 800°C and 500°C ($t_{8/5}$) from 2 to 50 seconds. This range of cooling times corresponds to the cooling conditions in gas-tungsten arc girth welds in water wall tubing.

2. The microstructure in CGHAZ of Grade T23 and T24 steels is a mixture of bainite and martensite with hardness higher than 340 HV throughout the studied range of $t_{8/5}$ cooling times. The high hardness at faster cooling rates is related to the higher martensite content in the microstructure. Precipitation of carbides is a potential mechanism of hardening in the predominantly bainitic microstructure at slower cooling rates in these steels.

3. With decreasing the cooling rate, the microstructure in CGHAZ of Grade T22 steel gradually changes from a mixture of martensite and bainite to predominantly bainitic with allotriomorphic ferrite. This corresponds to a moderate reduction in hardness from 340 HV to 300 HV.
4. In Grade T12 steel, the microstructure of CGHAZ rapidly changes from a mixture of martensite and bainite with hardness of 340 HV to bainitic and to a mixture of bainite with idiomorphic and allotriomorphic ferrite with hardness lower than 230 HV.

5. The hardness in the CGHAZ of Grade T22, T23, and T24 steel welds cannot be reduced below 300 HV by controlling the weld cooling rate. In Grade T12 steel welds, CGHAZ hardness lower than 300 HV can be easily achieved by keeping the $t_{8/5}$ cooling time above 5 seconds.
BIBLIOGRAPHY


APPENDIX A: SUSCEPTIBILITY TO SRC CRACKING
A.1 The OSU SRC Test – Simulated CGHAZ, T24

A.1.1 SRC Test at 600°C (T24)

Figure 97: Grade T24, simulated CGHAZ, longitudinal section, ductile failure, test temperature 600°C, $\sigma_{\text{failure}} = 815$ MPa, $\varepsilon_{\text{failure}} = 0.325$ (pulled to failure)
Figure 98: Grade T24, simulated CGHAZ, longitudinal section, elongated grains visible near fracture surface, test temperature 600°C, $\sigma_{\text{failure}} = 815$ MPa, $\varepsilon_{\text{failure}} = 0.325$ (pulled to failure)
Figure 99: Grade T24, simulated CGHAZ, force and temperature versus time, test temperature 600°C, $\sigma_{\text{failure}} = 815$ MPa, $\epsilon_{\text{failure}} = 0.325$ (pulled to failure)
Figure 100: Grade T24, simulated CGHAZ, stress and strain versus time, test temperature 600°C, $\sigma_{\text{failure}} = 815$ MPa, $\varepsilon_{\text{failure}} = 0.325$ (pulled to failure)
Figure 101: Grade T24, simulated CGHAZ, stress versus strain, test temperature

$600^\circ$C, $\sigma_{\text{failure}} = 815$ MPa, $\varepsilon_{\text{failure}} = 0.325$ (pulled to failure)
A.1.2 SRC Test at 650°C (T24)

Figure 102: Grade T24, simulated CGHAZ, longitudinal section, mostly brittle failure, test temperature 650°C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
Figure 103: Grade T24, simulated CGHAZ, longitudinal section, some intergranular cracking visible, slight elongation of some grains, test temperature 650°C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
Figure 104: Grade T24, simulated CGHAZ, SEM - Mainly intergranular failure, some ductility present, unidentified blocky particles, test temperature 650°C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
Figure 105: Grade T24, simulated CGHAZ, SEM – Ductile dimples, unidentified blocky particles, test temperature 650°C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
Figure 106: Grade T24, simulated CGHAZ, force and temperature versus time, test temperature 650°C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
Figure 107: Grade T24, simulated CGHAZ, stress and strain versus time, test

temperature 650°C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
Figure 108: Grade T24, simulated CGHAZ, stress versus strain, test temperature

$650^\circ$C, $\sigma_{\text{failure}} = 669$ MPa, $\varepsilon_{\text{failure}} = 0.011$ (pulled to failure)
A.1.3 SRC Test at 675°C (T24)

Figure 109: Grade T24, simulated CGHAZ, longitudinal section, brittle failure, test temperature 675°C, $\sigma_{\text{failure}} = 390$ MPa, $\varepsilon_{\text{failure}} = 0.007$ (failed on holding after 3.54 hours)
Figure 110: Grade T24, simulated CGHAZ, longitudinal section, intergranular cracking, test temperature 675°C, $\sigma_{\text{failure}} = 390$ MPa, $\varepsilon_{\text{failure}} = 0.007$ (failed on holding after 3.54 hours)
Figure 111: Grade T24, simulated CGHAZ, longitudinal section, intergranular cracking, test temperature 675°C, $\sigma_{\text{failure}} = 390$ MPa, $\varepsilon_{\text{failure}} = 0.007$ (failed on holding after 3.54 hours)
Figure 112: Grade T24, simulated CGHAZ, force and temperature versus time, test temperature 675°C, $\sigma_{\text{failure}} = 390$ MPa, $\varepsilon_{\text{failure}} = 0.007$ (failed on holding after 3.54 hours)
Figure 113: Grade T24, simulated CGHAZ, stress and strain versus time, test temperature 675°C, $\sigma_{\text{failure}} = 390$ MPa, $\varepsilon_{\text{failure}} = 0.007$ (failed on holding after 3.54 hours)
Figure 114: Grade T24, simulated CGHAZ, stress versus strain, test temperature

$675^\circ$C, $\sigma_{\text{failure}} = 390$ MPa, $\varepsilon_{\text{failure}} = 0.007$ (failed on holding after 3.54 hours)
A.1.4 SRC Test at 700°C (T24)

Figure 115: Grade T24, simulated CGHAZ, longitudinal section, brittle failure, test temperature 700°C, $\sigma_{\text{failure}} = 406$ MPa, $\varepsilon_{\text{failure}} = 0.0007$ (failed on holding after 11 minutes)
Figure 116: Grade T24, simulated CGHAZ, longitudinal section, intergranular cracking, test temperature 700°C, $\sigma_{\text{failure}} = 406$ MPa, $\varepsilon_{\text{failure}} = 0.0007$ (failed on holding after 11 minutes)
Figure 117: Grade T24, simulated CGHAZ, intergranular cracking, unidentified particles present, test temperature 700°C, $\sigma_{\text{failure}} = 406$ MPa, $\varepsilon_{\text{failure}} = 0.0007$ (failed on holding after 11 minutes)
Figure 118: Grade T24, simulated CGHAZ, force and temperature versus time, test temperature 700°C, $\sigma_{\text{failure}} = 406$ MPa, $\varepsilon_{\text{failure}} = 0.0007$ (failed on holding after 11 minutes)
Figure 119: Grade T24, simulated CGHAZ, stress and strain versus time, test temperature 700°C, $\sigma_{\text{failure}} = 406$ MPa, $\varepsilon_{\text{failure}} = 0.0007$ (failed on holding after 11 minutes)
Figure 120: Grade T24, simulated CGHAZ, stress versus strain, test temperature

700°C, $\sigma_{\text{failure}} = 406$ MPa, $\varepsilon_{\text{failure}} = 0.0007$ (failed on holding after 11 minutes)
A.1.5 SRC Test at 725°C (T24)

Figure 121: Grade T24, simulated CGHAZ, longitudinal section, brittle failure, test temperature 725°C, $\sigma_{\text{failure}} = 385$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at 725°C)
Figure 122: Grade T24, simulated CGHAZ, longitudinal section, brittle failure, test temperature 725°C, $\sigma_{\text{failure}} = 385$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at 725°C)
Figure 123: Grade T24, simulated CGHAZ, force and temperature versus time, test temperature $725^\circ$C, $\sigma_{\text{failure}} = 385$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at $725^\circ$C)
Figure 124: Grade T24, simulated CGHAZ, stress and strain versus time, test temperature 725°C, \( \sigma_{\text{failure}} = 385 \) MPa, \( \varepsilon_{\text{failure}} = 0 \) (failed on heating at 725°C)
Figure 125: Grade T24, simulated CGHAZ, stress versus strain, test temperature

$725^\circ C$, $\sigma_{\text{failure}} = 385$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at $725^\circ C$)
A.1.6 SRC Test at 729°C (T24)

Figure 126: Grade T24, simulated CGHAZ, longitudinal section, brittle failure, test temperature 729°C, $\sigma_{\text{failure}} = 361$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at 729°C)
Figure 127: Grade T24, simulated CGHAZ, longitudinal section, brittle failure, test temperature 729°C, \( \sigma_{\text{failure}} = 361 \text{ MPa} \), \( \varepsilon_{\text{failure}} = 0 \) (failed on heating at 729°C)
Figure 128: Grade T24, simulated CGHAZ, force and temperature versus time, test temperature 729°C, $\sigma_{\text{failure}} = 361$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at 729°C)
Figure 129: Grade T24, simulated CGHAZ, stress and strain versus time, test temperature 729°C, $\sigma_{\text{failure}} = 361$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at 729°C)
Figure 130: Grade T24, simulated CGHAZ, stress versus strain, test temperature

$729^\circ C$, $\sigma_{\text{failure}} = 361$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at $729^\circ C$)
A.2 The OSU SRC Test – 3-Pass Welds, T24, applied stress at RT - 778 MPa

A.2.1 SRC Test at 600°C (T24)

Figure 131: Grade T24, 3-pass weld, longitudinal section, test temperature 600°C,

\[ \sigma_{\text{failure}} = 819 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.27 \text{ (pulled to failure after 12 hours holding)} \]
Figure 132: Grade T24, 3-pass weld, longitudinal section, test temperature 600°C,

$\sigma_{\text{failure}} = 819$ MPa, $\varepsilon_{\text{failure}} = 0.27$ (pulled to failure after 12 hours holding)
Figure 133: Grade T24, 3-pass weld, force and temperature versus time, test temperature 600°C, $\sigma_{\text{failure}} = 819$ MPa, $\varepsilon_{\text{failure}} = 0.27$ (pulled to failure after 12 hours holding)
Figure 134: Grade T24, 3-pass weld, stress and strain versus time, test temperature 600°C, $\sigma_{\text{failure}} = 819$ MPa, $\varepsilon_{\text{failure}} = 0.27$ (pulled to failure after 12 hours holding)
Figure 135: Grade T24, 3-pass weld, stress versus strain, test temperature 600°C,

\[\sigma_{\text{failure}} = 819 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.27 \] (pulled to failure after 12 hours holding)
A.2.2 SRC Test at 650°C (T24)

Figure 136: Grade T24, 3-pass weld, longitudinal section, test temperature 650°C, 
$\sigma_{\text{failure}} = 133$ MPa, $\varepsilon_{\text{failure}} = 0.087$ (cracked on holding after 5.1 hours at 650°C, failed on holding after 6.3 hours)
Figure 137: Grade T24, 3-pass weld, longitudinal section, test temperature 650°C, 

$\sigma_{\text{failure}} = 133$ MPa, $\varepsilon_{\text{failure}} = 0.087$ (cracked on holding after 5.1 hours at 650°C, failed on holding after 6.3 hours)
Figure 138: Grade T24, 3-pass weld, force and temperature versus time, test temperature 650°C, $\sigma_{\text{failure}} = 133$ MPa, $\varepsilon_{\text{failure}} = 0.087$ (cracked on holding after 5.1 hours at 650°C, failed on holding after 6.3 hours)
Figure 139: Grade T24, 3-pass weld, stress and strain versus time, test temperature 650°C, $\sigma_{\text{failure}} = 133$ MPa, $\varepsilon_{\text{failure}} = 0.087$ (cracked on holding after 5.1 hours at 650°C, failed on holding after 6.3 hours)
Figure 140: Grade T24, 3-pass weld, stress versus strain, test temperature 650°C,

\[ \sigma_{\text{failure}} = 133 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.087 \] (cracked on holding after 5.1 hours at 650°C, failed on holding after 6.3 hours)
A.2.3 SRC Test at 700°C (T24)

Figure 141: Grade T24, 3-pass weld, longitudinal section, test temperature 700°C,

\[ \sigma_{\text{failure}} = 152 \text{ MPa, } \varepsilon_{\text{failure}} = 0.065 \text{ (failed on holding after 3.9 hours)} \]
Figure 142: Grade T24, 3-pass weld, longitudinal section, test temperature 700°C,

$$\sigma_{\text{failure}} = 152 \text{ MPa}, \varepsilon_{\text{failure}} = 0.065$$ (failed on holding after 3.9 hours)
Figure 143: Grade T24, 3-pass weld, force and temperature versus time, test temperature 700°C, $\sigma_{\text{failure}} = 152$ MPa, $\varepsilon_{\text{failure}} = 0.065$ (failed on holding after 3.9 hours)
Figure 144: Grade T24, 3-pass weld, stress and strain versus time, test temperature

700°C, \( \sigma_{\text{failure}} = 152 \text{ MPa} \), \( \varepsilon_{\text{failure}} = 0.065 \) (failed on holding after 3.9 hours)
Figure 145: Grade T24, 3-pass weld, stress versus strain, test temperature 700°C,

\[ \sigma_{\text{failure}} = 152 \text{ MPa}, \quad \varepsilon_{\text{failure}} = 0.065 \] (failed on holding after 3.9 hours)
A.2.4 SRC Test at 750°C (T24)

Figure 146: Grade T24, 3-pass weld, longitudinal section, test temperature 750°C, 
$\sigma_{\text{failure}} = 132$ MPa, $\varepsilon_{\text{failure}} = 0.089$ (cracked on heating at 707°C, pulled to failure after 8 hours)
Figure 147: Grade T24, 3-pass weld, longitudinal section, test temperature 750°C, 
$\sigma_{\text{failure}} = 132$ MPa, $\epsilon_{\text{failure}} = 0.089$ (cracked on heating at 707°C, pulled to failure after 8 hours)
Figure 148: Grade T24, 3-pass weld, force and temperature versus time, test temperature 750°C, $\sigma_{\text{failure}} = 132$ MPa, $\varepsilon_{\text{failure}} = 0.089$ (cracked on heating at 707°C, pulled to failure after 8 hours)
Figure 149: Grade T24, 3-pass weld, stress and strain versus time, test temperature 750°C, \( \sigma_{\text{failure}} = 132 \text{ MPa}, \varepsilon_{\text{failure}} = 0.089 \) (cracked on heating at 707°C, pulled to failure after 8 hours)
Figure 150: Grade T24, 3-pass weld, stress versus strain, test temperature 750°C,

$\sigma_{\text{failure}} = 132 \text{ MPa}, \varepsilon_{\text{failure}} = 0.089$ (cracked on heating at 707°C, pulled to failure after 8 hours)
A.3 The OSU SRC Test, 3-pass welds, T23

A.3.1 SRC Test at 625°C (T23)

![Graph showing force and temperature versus time](image)

**Figure 151:** Grade T23, 3-pass weld, force and temperature versus time, test temperature 625°C, $\sigma_{\text{failure}} = 670$ MPa, $\varepsilon_{\text{failure}} = 0.01$ (pulled to failure)
Figure 152: Grade T23, 3-pass weld, stress and strain versus time, test temperature

$625^\circ\text{C}, \sigma_{\text{failure}} = 670 \text{ MPa}, \varepsilon_{\text{failure}} = 0.01$ (pulled to failure)
Figure 153: Grade T23, 3-pass weld, stress versus strain, test temperature 625°C,

\[ \sigma_{\text{failure}} = 670 \text{ MPa}, \quad \varepsilon_{\text{failure}} = 0.01 \text{ (pulled to failure)} \]
A.3.2 SRC Test at 650°C (T23)

Figure 154: Grade T23, 3-pass weld, force and temperature versus time, test temperature 650°C, $\sigma_{\text{failure}} = 540$ MPa, $\varepsilon_{\text{failure}} = 0.02$ (pulled to failure after 12 hours)
Figure 155: Grade T23, 3-pass weld, stress and strain versus time, test temperature

$650^\circ C, \sigma_{\text{failure}} = 540$ MPa, $\varepsilon_{\text{failure}} = 0.02$ (pulled to failure after 12 hours)
Figure 156: Grade T23, 3-pass weld, stress versus strain, test temperature 650°C,

\[\sigma_{\text{failure}} = 540 \text{ MPa}, \varepsilon_{\text{failure}} = 0.02\) (pulled to failure after 12 hours)
A.3.3 SRC Test at 650°C (T23 - repeat)

Figure 157: Grade T23, 3-pass weld, force and temperature versus time, test temperature 650°C, $\sigma_{\text{failure}} = 191$ MPa, $\varepsilon_{\text{failure}} = 0.047$ (failed on holding after 1.69 hours)
Figure 158: Grade T23, 3-pass weld, stress and strain versus time, test temperature 650°C, $\sigma_{\text{failure}} = 191$ MPa, $\varepsilon_{\text{failure}} = 0.047$ (failed on holding after 1.69 hours)
Figure 159: Grade T23, 3-pass weld, stress versus strain, test temperature 650°C,

\[ \sigma_{\text{failure}} = 191 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.047 \] (failed on holding after 1.69 hours)
A.3.4 SRC Test at 650°C (T23 – repeat 2)

Figure 160: Grade T23, 3-pass weld, force and temperature versus time, test temperature 650°C, $\sigma_{\text{failure}} = 334$ MPa, $\varepsilon_{\text{failure}} = 0.01$ (failed on holding after 0.91 hours)
Figure 161: Grade T23, 3-pass weld, stress and strain versus time, test temperature 650°C, \( \sigma_{\text{failure}} = 334 \text{ MPa}, \varepsilon_{\text{failure}} = 0.01 \) (failed on holding after 0.91 hours)
Figure 162: Grade T23, 3-pass weld, stress versus strain, test temperature 650°C,

\[ \sigma_{\text{failure}} = 334 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.01 \text{ (failed on holding after 0.91 hours)} \]
A.3.5 SRC Test at 700°C (T23)

Figure 163: Grade T23, 3-pass weld, force and temperature versus time, test temperature 700°C, $\sigma_{\text{failure}} = 87$ MPa, $\varepsilon_{\text{failure}} = 0.068$ (failed on holding after 6.9 hours)
Figure 164: Grade T23, 3-pass weld, stress and strain versus time, test temperature

700°C, $\sigma_{\text{failure}} = 87$ MPa, $\varepsilon_{\text{failure}} = 0.068$ (failed on holding after 6.9 hours)
Figure 165: Grade T23, 3-pass weld, stress versus strain, test temperature $700^\circ$C,

$\sigma_{\text{failure}} = 87$ MPa, $\varepsilon_{\text{failure}} = 0.068$ (failed on holding after 6.9 hours)
A.3.6 SRC Test at 700°C (T23 - repeat)

Figure 166: Grade T23, 3-pass weld, force and temperature versus time, test temperature 700°C, $\sigma_{\text{failure}} = 192$ MPa, $\varepsilon_{\text{failure}} = 0.029$ (failed on holding after 7 minutes)
Figure 167: Grade T23, 3-pass weld, stress and strain versus time, test temperature 700°C, $\sigma_{\text{failure}} = 192$ MPa, $\varepsilon_{\text{failure}} = 0.029$ (failed on holding after 7 minutes)
Figure 168: Grade T23, 3-pass weld, stress versus strain, test temperature 700°C,

\[ \sigma_{\text{failure}} = 192 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.029 \text{ (failed on holding after 7 minutes)} \]
A.3.7 SRC Test at 742°C (T23)

Figure 169: Grade T23, 3-pass weld, force and temperature versus time, test temperature 742°C, $\sigma_{\text{failure}} = 150$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating at 742°C)
Figure 170: Grade T23, 3-pass weld, stress and strain versus time, test temperature

742°C, $\sigma_{\text{failure}} = 150$ MPa, $\varepsilon_{\text{failure}} = 0$ (failed on heating)
Figure 171: Grade T23, 3-pass weld, stress versus strain, test temperature 742°C,

\[ \sigma_{\text{failure}} = 150 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0 \text{ (failed on heating)} \]
A.4 The OSU SRC Test, 3-pass welds, T22

A.4.1 SRC Test at 600°C (T22)

Figure 172: Grade T22, 3-pass weld, force and temperature versus time, test temperature 600°C, $\sigma_{\text{failure}} = 572$ MPa, $\varepsilon_{\text{failure}} = 0.043$ (pulled to failure)
Figure 173: Grade T22, 3-pass weld, stress and strain versus time, test temperature

600°C, $\sigma_{\text{failure}} = 572$ MPa, $\varepsilon_{\text{failure}} = 0.043$ (pulled to failure)
Figure 174: Grade T22, 3-pass weld, stress versus strain, test temperature 600°C,

\[ \sigma_{\text{failure}} = 572 \text{ MPa}, \, \varepsilon_{\text{failure}} = 0.043 \text{ (pulled to failure)} \]

A.4.2 SRC Test at 650°C (T22)
Figure 175: Grade T22, 3-pass weld, longitudinal section, test temperature 650°C,

σ_{\text{failure}} = 63 \text{ MPa}, \varepsilon_{\text{failure}} = 0.209 \text{ (failed on holding after 5.76 hours)}
Figure 176: Grade T22, 3-pass weld, longitudinal section, test temperature 650°C,

\[ \sigma_{\text{failure}} = 63 \text{ MPa, } \varepsilon_{\text{failure}} = 0.209 \text{ (failed on holding after 5.76 hours)} \]
Figure 177: Grade T22, 3-pass weld, force and temperature versus time, test temperature 650°C, $\sigma_{\text{failure}} = 63$ MPa, $\varepsilon_{\text{failure}} = 0.209$ (failed on holding after 5.76 hours)
Figure 178: Grade T22, 3-pass weld, stress and strain versus time, test temperature 650°C, $\sigma_{\text{failure}} = 63$ MPa, $\varepsilon_{\text{failure}} = 0.209$ (failed on holding after 5.76 hours)
Figure 179: Grade T22, 3-pass weld, stress versus strain, test temperature 650°C,

\[ \sigma_{\text{failure}} = 63 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.209 \text{ (failed on holding after 5.76 hours)} \]

A.4.3 SRC Test at 700°C (T22)
Figure 180: Grade T22, 3-pass weld, longitudinal section, test temperature 700°C,

\[ \sigma_{\text{failure}} = 84 \text{ MPa}, \ v_{\text{failure}} = 0.138 \] (failed on holding after 40 minutes)
Figure 181: Grade T22, 3-pass weld, longitudinal section, test temperature 700°C,

\[ \sigma_{\text{failure}} = 84 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.138 \] (failed on holding after 40 minutes)
Figure 182: Grade T22, 3-pass weld, force and temperature versus time, test temperature 700°C, $\sigma_{\text{failure}} = 84$ MPa, $\varepsilon_{\text{failure}} = 0.138$ (failed on holding after 40 minutes)
Figure 183: Grade T22, 3-pass weld, stress and strain versus time, test temperature

700°C, $\sigma_{\text{failure}} = 84$ MPa, $\varepsilon_{\text{failure}} = 0.138$ (failed on holding after 40 minutes)
Figure 184: Grade T22, 3-pass weld, stress versus strain, test temperature 700°C,

\[ \sigma_{\text{failure}} = 84 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.138 \] (failed on holding after 40 minutes)
A.5 The OSU SRC Test, 3-pass welds, T12

A.5.1 SRC Test at 650°C (T12)

Figure 185: Grade T12, 3-pass weld, longitudinal section, test temperature 650°C,

\[ \sigma_{\text{failure}} = 122 \text{ MPa}, \ \epsilon_{\text{failure}} = 0.193 \text{ (pulled to failure)} \]
Figure 186: Grade T12, 3-pass weld, longitudinal section, test temperature 650°C,

$\sigma_{\text{failure}} = 122$ MPa, $\varepsilon_{\text{failure}} = 0.193$ (pulled to failure)
Figure 187: Grade T12, 3-pass weld, force and temperature versus time, test

temperature 650°C, $\sigma_{\text{failure}} = 122$ MPa, $\varepsilon_{\text{failure}} = 0.193$ (pulled to failure)
Figure 188: Grade T12, 3-pass weld, stress and strain versus time, test temperature 650°C, $\sigma_{\text{failure}} = 122$ MPa, $\varepsilon_{\text{failure}} = 0.193$ (pulled to failure)
Figure 189: Grade T12, 3-pass weld, stress versus strain, test temperature 650°C,

\[ \sigma_{\text{failure}} = 122 \text{ MPa}, \quad \varepsilon_{\text{failure}} = 0.193 \text{ (pulled to failure)} \]
A.5.2 SRC Test at 700°C (T12)

Figure 190: Grade T12, 3-pass weld, longitudinal section, test temperature 700°C,

$\sigma_{\text{failure}} = 78$ MPa, $\varepsilon_{\text{failure}} = 0.29$ (pulled to failure)
Figure 191: Grade T12, 3-pass weld, longitudinal section, test temperature 700°C,

\[ \sigma_{\text{failure}} = 78 \text{ MPa}, ~ \varepsilon_{\text{failure}} = 0.29 \text{ (pulled to failure)} \]
Figure 192: Grade T12, 3-pass weld, force and temperature versus time, test temperature 700°C, \( \sigma_{\text{failure}} = 78 \text{ MPa}, \ \varepsilon_{\text{failure}} = 0.29 \) (pulled to failure)
Figure 193: Grade T12, 3-pass weld, stress and strain versus time, test temperature

$700^\circ C$, $\sigma_{\text{failure}} = 78$ MPa, $\varepsilon_{\text{failure}} = 0.29$ (pulled to failure)
Figure 194: Grade T12, 3-pass weld, stress versus strain, test temperature 700°C,

\[ \sigma_{\text{failure}} = 78 \text{ MPa}, \quad \varepsilon_{\text{failure}} = 0.29 \text{ (pulled to failure)} \]
A.5.3 SRC Test at 750°C (T12)

Figure 195: Grade T12, 3-pass weld, longitudinal section, test temperature 750°C,

\[ \sigma_{\text{failure}} = 83 \text{ MPa}, \varepsilon_{\text{failure}} = 0.292 \text{ (pulled to failure)} \]
Figure 196: Grade T12, 3-pass weld, longitudinal section, test temperature 750°C,

\[ \sigma_{\text{failure}} = 83 \text{ MPa, } \varepsilon_{\text{failure}} = 0.292 \text{ (pulled to failure)} \]
Figure 197: Grade T12, 3-pass weld, force and temperature versus time, test temperature 750°C, $\sigma_{\text{failure}} = 83$ MPa, $\varepsilon_{\text{failure}} = 0.292$ (pulled to failure)
Figure 198: Grade T12, 3-pass weld, stress and strain versus time, test temperature 750°C, $\sigma_{\text{failure}} = 83$ MPa, $\varepsilon_{\text{failure}} = 0.292$ (pulled to failure)
Figure 199: Grade T12, 3-pass weld, stress versus strain, test temperature 750°C,

\[ \sigma_{\text{failure}} = 83 \text{ MPa}, \varepsilon_{\text{failure}} = 0.292 \text{ (pulled to failure)} \]