Declaration

I hereby declare that the work presented in this thesis titled "**Investigation on Dissimilar Welded Joint between Incoloy 800HT and Heat-Resistant P91 Steel for Advanced Ultra-Supercritical Boiler Applications**", submitted to the Indian Institute of Technology Jodhpur in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of Dr. Ankur Gupta and Dr. Chandan Pandey. The contents of this thesis, in whole or in parts, have not been submitted to and will not be submitted by me to any other Institute or University in India or abroad for the award of any degree or diploma.

Vishwa Bhanu
P19ME213

Certificate

This is to certify that the thesis titled "**Investigation on Dissimilar Welded Joint between Incoloy 800HT and Heat-Resistant P91 Steel for Advanced Ultra-Supercritical Boiler Applications**", submitted by Vishwa Bhanu (P19ME213) to the Indian Institute of Technology Jodhpur for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work done by him under our supervision. To the best of our knowledge, the contents of this report, in whole or in parts, have not been submitted to any other Institute or University in India or abroad for the award of any degree or diploma.

Dr. Ankur Gupta
Associate Professor
Indian Institute of Technology Jodhpur

Dr. Chandan Pandey
Associate Professor
Indian Institute of Technology Jodhpur

Abstract

This thesis delves into the crucial aspect of welding Incoloy 800HT and P91 steel, fundamental materials in advanced ultra-supercritical (AUSC) reactors aimed at enhancing power generation efficiency while minimizing CO_2 emissions. The study primarily focuses on dissimilar metal welding (DMW) to unite these materials and addresses the complex challenges associated with DMW, such as phase transformations, creep-related issues, and microstructural heterogeneity. Various welding techniques, including gas tungsten arc welding (GTAW), electron beam welding (EBW), shielded metal arc welding (SMAW), and activated tungsten inert gas (A-TIG) welding, are explored to determine their efficacy in creating robust and durable joints.

The investigation revolves around understanding the microstructural alterations, mechanical behaviors, and optimal welding parameters necessary to refine the welding process. Advanced characterization tools viz., field emission scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (FESEM/EDS), electron probe micro-analysis (EPMA), electron backscatter diffraction microscopy (EBSD), transmission electron microscopy (TEM), and X-ray diffraction (XRD) are utilized to scrutinize the welds' microstructural features in detail. Mechanical evaluations encompass room temperature tensile testing, high-temperature tensile testing (up to 650 °C), Charpy impact toughness testing, fractography, residual stress measurements (using deep hole drill method), and microhardness measurements. These tests are pivotal in correlating microstructural transformations with the mechanical integrity of the DMW.

Furthermore, the study investigates post-weld heat treatment (PWHT) as a potential solution to mitigate heterogeneous microstructures in the P91 heat-affected zone (HAZ) resulting from the DMW process. The thesis emphasizes the importance of achieving joint integrity and performance, particularly in high-temperature operating conditions typical of AUSC reactors. The findings underscore the superiority of A-TIG welding over conventional methods, exhibiting enhanced weld quality and superior mechanical properties. A-TIG welding is recommended as the preferred approach for joining Incoloy 800HT and P91 steel due to its ability to produce fine-grained textures, evenly distributed precipitates, improved mechanical strength, and reduced risk of microstructural degradation.

In summary, this research contributes significantly to the understanding of DMW challenges, weld quality enhancement, and performance optimization for critical applications in AUSC reactor technology, ensuring safe and efficient power generation processes.

...

Acknowledgements

First and foremost, I thank my Ph.D. Thesis Supervisors, *Dr. Ankur Gupta and Dr. Chandan Pandey,* for providing inestimable guidance, encouragement, moral support and assistance during the research work. Their observations and comments helped me to establish the overall direction of the research and to move forward with investigation in depth. I am very grateful for their motivation, enthusiasm, and immense knowledge in welding technology. The successful and timely completion of the research work is due to their constant inspiration and extraordinary vision. Also, I am indebted to the Members of the Doctoral Committee, *Dr. Abir Bhattacharyya, Dr. Atul Kumar Sharma* and *Dr. Arun Kumar R*, for their enthusiastic and continued guidance during the research work.

I would also extend my gratitude to Dr. Ravi Shanker Vidyarthy for sharing the skill of Activated-TIG welding. I am grateful for the generosities of my friends Rahul Choudhary, Sachin Kumar, Ashish Rehal, Amit Kumar Dhiman, Gaurav Kumar Dak, Vinay Kishnani, Yogesh Sharma, Alok Mandal, Sanjay Singh, and Pavan. I am thankful to Mr. Mukesh for helping me with the electron microscopy at IIT Jodhpur central research facility.

I acknowledge and thank my family members for the patience and love with which they ushered on me. I pay respects to my *parents* for all their *love, sacrifices, and blessings…*

Vishwa Bhanu
Ph.D. Student

Contents

		page
Abstract		v
Acknowledgements		vi
Contents		viii
List of Figures		xi
List of Tables		xvii
List of Symbols		xviii
List of Abbreviations		xix

Chapter 1: Introduction

Chapter 2: Literature Review

2.1	Problems related to the joining of dissimilar metals	5
2.2	Issue of residual stresses generated in the DWJs	7
2.3	High-temperature tensile strength and behavior of DWJs	8
2.4	Need of the post weld heat treatment (PWHT) process in DWJs	8
2.5	Comparison of the A-TIG process with the conventional welding trends	9
2.6	Literature review regarding A-TIG welding technique and flux selection	12
2.7	Buttering layer welding technique	15
2.8	Summary of the past work	15
2.9	Research gaps in the literature review	15
2.10	Research objectives	16
2.11	Research methodology opted for the present work	16

Chapter 3: Material and Experimental Details

3.1	Base metals	17
3.2	Edge preparation	21
3.3	Welding procedures and parameters	22
	3.3.1 Radiant energy welding processes	22
	3.3.2 Shielded metal arc welding (SMAW) process	22
	3.3.3 Multipass-tungsten inert gas (M-TIG) welding processes	23
	3.3.4 Autogenous-tig welding processes (with interlayers)	24
	3.3.5 M-TIG Welding Processes Using the Buttering Layer Technique	24
	3.3.6 Activated-TIG (A-TIG) welding process	24
3.4	Post weld heat treatment (PWHT)	25
3.5	Sample preparation	25
3.6	Residual stress measurements	26

Chapter 4: Autogenous welding techniques

4.1	Laser beam welding (LBW)	29
	4.1.1 Macroscopic observations	29
	4.1.2 Heat Affected Zone (HAZ) microstructure characterization	30
	4.1.3 Weld fusion zone (WFZ) microstructure characterization	32
	4.1.4 Tensile properties	38
	4.1.5 Microhardness properties	40
	4.1.6 Charpy impact toughness	41
4.2	Electron beam welding (EBW)	42
	4.2.1 Macroscopic observations	42
	4.2.2 Weld fusion zone (WFZ) microstructure characterization	42
	4.2.3 Tensile properties	49
	4.2.4 Microhardness properties	51
	4.2.5 Charpy impact toughness	54
4.3	Autogenous tungsten inert gas (TIG) welding with interlayers	55
	4.3.1 Macroscopic observations	55

4.3.2 Heat affected zone (HAZ) microstructure characterization 55
4.3.3 Weld fusion zone (WFZ) microstructure characterization 57
4.3.4 Tensile strength properties 58
4.3.5 Microhardness properties 59
4.3.6 Charpy impact toughness properties 60

Chapter 5: Multipass-Tungsten Inert Gas (M-TIG) Welding Technique

5.1 Using AWSER90S–B9 filler (p91) *61*
5.1.1 Macroscopic observations *61*
5.1.2 Weld fusion zone (WFZ) microstructure Characterization *61*
5.1.3 Residual stresses *65*
5.1.4 Tensile properties *66*
5.1.5 Microhardness properties *67*
5.1.6 Charpy impact toughness *69*
5.2 Using ERNiCr-3 (INCONEL 82) *70*
5.2.1 Macroscopic observations *70*
5.2.2 Weld fusion zone (WFZ) microstructure characterization *71*
5.2.3 Residual stresses *74*
5.2.4 Tensile properties *75*
5.2.5 Microhardness properties *76*
5.2.6 Charpy impact toughness *78*
5.3 Using ERNiCrMo-3 (INCONEL 625) *79*
5.3.1 Macroscopic observations *79*
5.3.2 Weld fusion zone (WFZ) microstructure characterization *79*
5.3.3 Residual stresses *81*
5.3.4 Tensile properties *82*
5.3.5 Microhardness properties *83*
5.3.6 Charpy impact toughness *84*
5.4 Using ERNiCrCoMo-1 (INCONEL 617) *85*
5.4.1 Macroscopic observations *85*
5.4.2 Heat affected zone (HAZ) microstructure characterization *86*
5.4.3 Weld fusion zone (WFZ) microstructure characterization *89*
5.4.4 Residual stresses *94*
5.4.5 Tensile properties *95*
5.4.6 Microhardness properties *97*
5.4.7 Charpy impact toughness *99*
5.5 Using buttering welding technique *100*
5.5.1 Heat affected zone (HAZ) microstructure characterization *101*
5.5.2 Weld fusion zone (WFZ) microstructure characterization *102*
5.5.3 Electron backscatter diffraction (EBSD) analysis *105*
5.5.4 Tensile properties *107*
5.5.5 Microhardness properties *110*
5.5.6 Charpy impact toughness *111*

Chapter 6: Shielded Metal Arc Welding (SMAW) Technique

6.1 Macroscopic observations *113*
6.2 Weld interface and weld fusion zone (WFZ) microstructure characterization *113*
6.3 Tensile properties *118*
6.4 Microhardness properties *119*
6.5 Charpy impact toughness *120*

Chapter 7: Activated-Tungsten inert gas (A-TIG) welding

7.1 Bead-on-plate experiments *123*
7.1.1 Macroscopic observations *124*
7.2 *P91 similar welded joint using A-TIG welding technique* *126*
7.2.1 Macroscopic observations *126*
7.2.2 Heat affected zone (HAZ) microstructure characterization *126*

7.2.3 Weld fusion zone (WFZ) microstructure characterization 128
7.2.4 Tensile properties 130
7.2.5 Microhardness properties 132
7.2.6 Charpy impact toughness 133
7.3 Incoloy 800HT similar welded joint using A-TIG welding technique 134
7.3.1 Macroscopic observations 134
7.3.2 Weld fusion zone (WFZ) microstructure characterization 134
7.3.3 Tensile properties 136
7.3.4 Microhardness properties and Charpy impact toughness 137
7.4 Dissimilar weld joint (DWJ) between p91 and Incoloy 800HT using A-TIG welding technique 137
7.4.1 Macroscopic observations 137
7.4.2 P91 weld interface microstructure characterization 139
7.4.3 Incoloy 800HT weld interface microstructure characterization 140
7.4.4 Weld fusion zone (WFZ) microstructure characterization 142
7.4.5 Tensile properties 145
7.4.6 Microhardness properties 147
7.4.7 Charpy impact toughness 147

Chapter 8: Conclusions and Scope of Future Work

Annexure A

Appendix A: List of Publication 153
Appendix B: Summary of Tensile Strength 155
Appendix C: Summary of Microhardness and Charpy Impact Toughness 156

References

List of Figures

Figures No.	Title	Page No.
1.1	*Impact of dissimilar weld joint development on CO_2 emissions (Barnes, 2018)*	2
1.2	Development of 9-12% Cr steel and Ni-Fe-Cr alloy (David et al., 2013)	3
1.3	Representation of a dissimilar weld joint (DWJ) structure for connecting the pipe-nozzle of a reactor pressure vessel to safe-end pipe (Hänninen et al., 2006)	4
2.1	(a) Schematic of conventional TIG arc mechanism, and (b) Schematic of A-TIG arc mechanism	11
2.2	Effect of change in coating density on the depth-to-width ratio (DWR) (Jayakrishnan and Chakravarthy, 2017)	12
2.3	Modified Ellingham Diagram (Hasegawa, 2014)	13
2.4	Schematics of welding arc fluctuation observed due to difference in conductivity 'k' while A-TIG welding (a) without flux, (b) with optimized flux, (c) schematic of arc diameter measurement location	14
3.1	(a) P91 base metal optical microstructure; (b) Incoloy 800HT base metal optical microstructure; (c) P91 base metal microstructure under SEM with EDS spectra of the precipitate; (d) Incoloy 800HT base metal microstructure under SEM with EDS spectra of the precipitate	18
3.2	Normal distribution of grain size observed in (a) P91 base metal and (b) Incoloy 800HT base metal	19
3.3	X-ray diffraction diagram for (a) as-received P91 (b) as-received Incoloy 800HT base metals	19
3.4	Equilibrium phase diagram for (a) P91 and (b) Incoloy 800HT base metals	19
3.5	P91 base metal (a) IPF map, (b) IQ + grain boundary map, (c) phase map, and Incoloy 800HT (d) IPF map, (e) IQ + grain boundary map, (f) phase map	20
3.6	Schematics representing groove geometries prepared for different welding techniques	21
3.7	Schematic representing the steps involved in the flux application process prior to A-TIG welding	25
3.8	(a-b) Heat treatment cycles and history of the base metals prior to and post-welding process	25
3.9	Schematic diagram for specimen dimensions extraction from the welded plates	26
3.10	(a) Residual stresses measurement locations (b) steps involved in deep hole drilling method of residual stresses measurement	27
4.1	Macrograph of the laser weld bead	29
4.2	P91 HAZs in AW condition: (a) CGHAZ (b) FGHAZ (c) ICHAZ; after PWHT (d) CGHAZ (e) FGHAZ (f) ICHAZ; ICHAZ at higher magnification showing the location for EDS spectrum for (g) AW (h) PWHT condition	31
4.3	(a) Incoloy 800HT HAZ in AW condition with EDS spectrum for precipitate observed in AW condition (b) Incoloy 800HT HAZ in PWHT condition with EDS spectrum for precipitate observed in PWHT condition	32
4.4	Optical image showing weld interface of (a) AW P91 side (b) AW Incoloy 800HT side (c) PWHT P91 side (d) PWHT Incoloy 800HT side	33
4.5	Line map EDS analyses along (a) AW P91 weld interface (b) AW Incoloy 800HT weld interface (c) PWHT P91 weld interface, and (d) PWHT Incoloy 800HT weld interface	34
4.6	Optical images for (a) WFZ in AW condition (b) top WFZ (c) WFZ mixed zone (d) bottom WFZ	35
4.7	Optical images for (a) WFZ in PWHT condition (b) top of the WFZ (c) WFZ mixed zone (d) bottom	36
4.8	SEM micrograph cracks in AW specimen WFZ and EDS spectra of precipitate observed in the dendritic core region	37
4.9	Line map EDS analysis across the interdendritic cores in the weld region	37
4.10	(a) Engineering stress-strain curves for performed tensile tests; SEM fractography micrographs of (b) standard AW specimen, (c) standard PWHT specimen, (d) sub-size AW specimen, (e) sub-size PWHT specimen	39
4.11	SEM micrograph for PWHT specimen (a) WFZ, (b) crack along SGB, (c) PWHT Incoloy 800HT weld interface, (d) crack along Type II fusion boundary	39

4.12	Microhardness variation obtained for AW and PWHT weldments	40
4.13	Samples fractured under Charpy impact testing from (a) WFZ (b) HAZ P91 (c) HAZ Incoloy 800HT (d) PWHT WFZ (e) PWHT HAZ P91 (f) PWHT Incoloy HAZ	41
4.14	SEM fractography micrograph of specimens broken during Charpy impact toughness test (a) AW (impact at WFZ), (b) PWHT (impact at WFZ)	41
4.15	(a) Electron beam welded plate in AW state (b) macrostructure of weld seam in AW state	42
4.16	(a) Stitched optical micrographs of electron beam weld (b-c) EDS line map spectrum across the weld bead	43
4.17	Optical micrographs of (a) P91 weld interface (near weld top) (b) WFZ (near weld top) (c) Incoloy 800HT weld interface (near weld top) (d) P91 weld interface (near weld center) (e) WFZ (near weld center) (f) Incoloy 800HT weld interface (near weld center) (g) P91 weld interface (near weld root) (h) WFZ (near weld root) (i) Incoloy 800HT weld interface (near weld root) (j) P91 weld interface (near weld center) (k) WFZ (near weld center) (l) Incoloy 800HT weld interface (near weld center)	44
4.18	EPMA qualitative analysis of P91 weld interface	45
4.19	EPMA qualitative analysis of Incoloy 800HT weld interface	46
4.20	EBSD scan at P91 weld interface : (a) IPF map (b) KAM map (c) phase map	47
4.21	EBSD scan at Incoloy 800HT weld interface : (a) IPF map (b) KAM map (c) phase map	47
4.22	FESEM micrograph and EDS spectrum of (a) WFZ in AW state (b) WFZ in PWHT state (c) dendrites in AW state WFZ (d) dendrites in PWHT state WFZ (e) elemental composition of spotted interdendritic particles in AW states WFZ (f) elemental composition of spotted interdendritic particles in PWHT states WFZ	49
4.23	(a) Fractured tensile specimens after testing and (b) plotted engineering stress-strain curves for base metals and tested tensile specimens	50
4.24	Fractography SEM micrographs of (a) AW state standard tensile specimen (b) PWHT state standard tensile specimen (c) AW state subsize tensile specimen (d) PWHT state subsize tensile specimen	51
4.25	Schematic representing the array design of microhardness indents taken	51
4.26	2D Microhardness contour profile plot of AW specimen	52
4.27	2D contour profile plot of microhardness across the specimen in PWHT state	53
4.28	V-notched Charpy impact toughness specimens (a) before testing (b) after testing	54
4.29	(a) Interlayers placement before welding (b) welding setup (c) weld macrograph	55
4.30	Micrographs of (a) CGHAZ (b) FGHAZ (c) ICHAZ	56
4.31	Micrographs of Incoloy 800HT HAZ with EDS	56
4.32	Micrographs of different WFZ areas (a) Near Incoloy 800HT weld interface (b) near weld center (c) near P91 weld interface	57
4.33	Micrograph of P91 weld interface with line mapping	58
4.34	Micrograph of Incoloy 800HT weld interface with line mapping	58
4.35	(a) Stress-strain plots (b) fractured surface micrograph	59
4.36	Microhardness variation plot	60
4.37	(a) Tested specimen for Charpy impact toughness (b) fractured surface micrograph	60
5.1	(a) Welded plate (b) weld bead macrograph	61
5.2	(a) Optical image of P91 weld interface in AW state (b) optical image of Incoloy 800HT weld interface in AW state (c) optical image of P91 weld interface in PWHT state (d) SEM image of Incoloy 800HT weld interface in PWHT state	62
5.3	(a) Line mapping spectrum in the SEM image of the P91 weld interface in the AW condition (b) SEM image of Incoloy 800HT weld interface in AW state with line mapping spectrum	63
5.4	(a) Optical view of WFZ in the AW condition (b) WFZ XRD-diffractogram in the AW state (c) SEM image of WFZ in AW state (d) EDS spectrum of the marked small area in the WFZ	63
5.5	Schaeffler plot to predict the WFZ microstructure (Schaeffler, 1949)	64
5.6	(a) PWHT-state optical representation of WFZ (b) SEM image of WFZ in AW state (c) after PWHT, the new precipitates in the WFZ were mapped out using area mapping	65
5.7	Residual stress distribution plot observed for WFZ in AW and PWHT states	66
5.8	(a) Extracted tensile specimens before tensile testing (b) broken tensile specimens after tensile testing marked with the location of failure (c) PWHT state standard tensile specimen SEM fractography image (d) PWHT state subsize tensile specimen SEM fractography image (e) engineering stress-strain curves for specimens subjected to tensile testing	67

5.9	Microhardness variation profile of the weldment in AW and PWHT states	68
5.10	(a) Extracted tensile specimens before tensile testing (b) broken tensile specimens after tensile testing marked with the location of failure (c) PWHT state standard tensile specimen SEM fractography image (d) PWHT state subsize tensile specimen SEM fractography image	69
5.11	Microstructure of the weld bead in the as-welded condition	70
5.12	Optical images showing different HAZ subzones in AW condition	70
5.13	Schematic representing angular distortion method	71
5.14	Weld interface optical images of (a) AW Incoloy 800HT (b) AW P91 (c) AW Incoloy 800HT AW at higher magnification (d) AW P91 at higher magnification	71
5.15	(a) SEM image for AW P91 weld interface (b) Line map EDS analyses across the P91weld interface (d) EPMA analysis for P91 weld interface	72
5.16	(a) SEM image for AW Incoloy 800HT weld interface (b) Line map EDS analyses across Incoloy 800HT weld interface (d) EPMA analysis for P91 weld interface	73
5.17	ERNiCr-3 filler-based DWJ: (a) WFZ optical image (b) WFZ optical image at higher magnification (c) SEM micrograph of WFZ and line EDS spectra across the interdendritic region (d) EPMA analysis of weld fusion zone	73
5.18	Residual stress variation profiles for (a) WFZ in AW and PWHT states (b) Incoloy 800HT HAZ in AW and PWHT states (c) P91 HAZ in AW and PWHT states	74
5.19	Fractured tensile samples and engineering stress-strain curves for different specimens	75
5.20	Fractured tensile specimen surface of (a) standard AW tensile specimen (b)subsize AW tensile specimen	76
5.21	Microhardness variation obtained for (a)AW condition across the P91-Incoloy 800HT DWJ (b) PWHT condition across the P91-Incoloy 800HT DWJ	77
5.22	Microhardness variation obtained for WFZ (top to bottom) in both AW and PWHT states	78
5.23	(a) Position of the notch in WFZ in AW state specimen and after fracture specimen (b) position of the notch in WFZ in PWHT state specimen and after fracture specimen	78
5.24	Fractured impact toughness specimens (a) AW condition surface (b) AW condition surface at higher magnification (a) PWHT condition surface (b) PWHT condition surface at higher magnification	78
5.25	(a) ERNiCrMo-3 filler-based DWJ in AW condition (b) ERNiCrMo-3 filler-based DWJ macrostructure	79
5.26	Stitched optical images of different HAZ subzones in AW condition	79
5.27	Stitched optical image of Incoloy 800HT weld interface and P91 weld interface of ERNiCrMo-3 filler-based DWJ in AW condition	80
5.28	(a) SEM micrograph for AW P91 weld interface of ERNiCrMo-3 filler-based DWJ with line map EDS analysis across the P91weld interface (b) SEM micrograph for AW Incoloy 800HT weld interface of ERNiCrMo-3 filler-based DWJ with line map EDS analysis across Incoloy 800HT weld interface	80
5.29	ERNiCrMo-3 filler (a-b) AW WFZ optical image (c) AW WFZ SEM image (d-e) PWHT WFZ optical image (f) PWHT WFZ SEM image (f1-6) EDS /elemental mapping images	81
5.30	Residual stress variation profiles for WFZ in AW and PWHT states of ERNiCrMo-3 filler-based DWJ	81
5.31	ERNiCr-3 filler-based DWJ fractured tensile and engineering stress-strain for different specimens of ERNiCrMo-3 filler-based DWJ	82
5.32	Fractured tensile specimen surface of (a) subsize AW tensile specimen of ERNiCrMo-3 filler-based DWJ (b) standard PWHT tensile specimen ERNiCrMo-3 filler-based DWJ	82
5.33	Microhardness variation obtained for (a) ERNiCrMo-3 filler-based DWJ in AW condition across the P91-Incoloy 800HT DWJ (b) ERNiCrMo-3 filler-based DWJ in PWHT condition across the P91-Incoloy 800HT DWJ	83
5.34	(a) V- notch at ERNiCrMo-3 filler WFZ in AW state specimen and after fracture specimen (b) V- notch at ERNiCrMo-3 filler WFZ in PWHT state specimen and after fracture specimen	84
5.35	Fractured impact toughness specimen surface of (a) AW ERNiCrMo-3 filler WFZ (b) PWHT ERNiCrMo-3 filler WFZ	85
5.36	(a) Welded plate in as-welded (AW) state (b) Macrostructure of the weld bead in the as-welded condition	85
5.37	Optical and SEM micrographs of different zones of AW P91 HAZ (a,d) CGHAZ (b,e) FGHAZ (c,f) ICHAZ	86
5.38	Optical and SEM micrographs of different zones of PWHT P91 HAZ (a) CGHAZ (b) FGHAZ (c) ICHAZ	87

5.39	Normal distribution of grain size observed in (a) AW P91 CGHAZ (b) PWHT P91 CGHAZ (c) AW P91 FGHAZ (d) PWHT P91 FGHAZ (e) AW P91 ICHAZ (f) PWHT P91 ICHAZ	88
5.40	(a) Optical image of Incoloy 800HT HAZ in AW condition (b) Optical image of Incoloy 800HT HAZ in PWHT condition (c) SE image of Incoloy 800HT HAZ in AW (d) SE image of Incoloy 800HT HAZ in PWHT condition	89
5.41	P91 weld interface in AW state optical images	90
5.42	(a) SEM image for AW P91 weld interface (b) Line map EDS analyses along the P91weld interface	91
5.43	EPMA analysis for P91 weld interface	91
5.44	Incoloy 800HT AW state weld interface optical images	92
5.45	(a) FESEM image for AW Incoloy 800HT weld interface (b) Line map EDS analyses along Incoloy 800HT weld interface	92
5.46	EPMA analysis for P91 weld interface	93
5.47	SEM micrograph of WFZ taken at (a) top AW WFZ region (b) center of AW WFZ (c) root of AW WFZ (d) top PWHT WFZ region (e) center of PWHT WFZ (f) root of PWHT WFZ	93
5.48	EPMA analysis for ERNiCrCoMo-1 WFZ of P91-Incoloy 800HT DWJ	94
5.49	Residual stress variation profiles for WFZ in AW and PWHT states	95
5.50	Fractured tensile samples and engineering stress-strain curves for different specimens	96
5.51	Fractured tensile specimen surface of (a) standard AW tensile specimen (b) subsize AW tensile specimen (c) standard PWHT tensile specimen (d) subsize PWHT tensile specimen	97
5.52	Microhardness variation obtained for AW condition across the P91-Incoloy 800HT DWJ	98
5.53	Microhardness variation obtained for PWHT condition across the P91-Incoloy 800HT DWJ	99
5.54	(a) Position of the notch in WFZ in AW state specimen and after fracture specimen (b position of the notch in WFZ in PWHT state specimen and after fracture specimen	100
5.55	(a) Fractured impact toughness specimens (a) fractured surface of AW specimen (b) fractured surface of AW specimen at higher magnification (c) fractured surface of PWHT specimen (d) fractured surface of PWHT specimen at a higher magnification	100
5.56	Micrographs of (a) P91 ICHAZ (b) P91 FGHAZ (c) P91 CGHAZ with EDS spectrum (d) Incoloy 800HT HAZ with EDS spectrum	102
5.57	Optical micrograph of (a) WFZ (b) P91 weld interface with buttering layers (c) weld bead macrograph (d) Incoloy 800HT weld interface with WFZ (e) WFZ and buttering interface	103
5.58	(a) FESEM micrograph of P91 weld interface with line mapping spectrum across the two different interfaces (b) FESEM micrograph of Incoloy 800HT weld interface with line mapping spectrum across the interface	104
5.59	FESEM micrograph of WFZ with area mapping	104
5.60	(a) TEM micrograph of WFZ with area mapping (b) TiC precipitate	105
5.61	FESEM micrograph of the SGB observed in the buttering region with area mapping	105
5.62	Incoloy 800HT weld interface (a) IPF map (b) IQ+grain boundary map (c) KAM map (d) phase map (e) GOS map; WFZ/buttering interface region (f) IPF map (g) IQ+grain boundary map (h) KAM map (i) phase map (j) GOS map; WFZ (k) IPF map (l) IQ+grain boundary map (m) KAM map (n) phase map (o) GOS map; P91 weld interface (p) IPF map (q) IQ+grain boundary map (r) KAM map (s) phase map (t) GOS map	107
5.63	(a) Schematics of the specimens prepared (b) fractured specimens	109
5.64	Engineering stress-strain curves for tested tensile specimens	109
5.65	Fractography micrograph of (a) BL-1 specimen fractured surface (b) BL-2 specimen fractured surface (c) HT (550°C) specimen fractured surface (d) HT (650°C) specimen fractured surface	110
5.66	Microhardness variation plot for the P91 and Incoloy 800HT DWJ	111
5.67	(a)Schematics of Charpy impact toughness specimens prepared (b) V-notch specimens after fracture (c) micrographs of specimen failed from the WFZ (d) micrographs of specimen failed from the buttering region	112
6.1	(a) Welded plate top face (b) welded plate bottom face (c) SMAW weld macrostructure	113
6.2	Optical micrographs of (a) Incoloy 800HT weld interface (near weld top) (b) WFZ (near weld top) (c) P91 weld interface (near weld top) (d) Incoloy 800HT weld interface (near weld center) (e) WFZ (near weld center) (f) P91 weld interface (near weld center) (g) Incoloy 800HT weld interface (near weld root) (h) WFZ (near weld root) (i) P91 weld interface (near weld root)	114
6.3	FESEM micrograph and EDS spectrum of (a) WFZ in AW state (b) WFZ in PWHT state (c)	115

spotted interdendritic particles in AW states WFZ (d) spotted interdendritic particles in PWHT states WFZ
6.4 EPMA qualitative analysis of P91 weld interface, Incoloy 800HT weld interface, and WFZ 116
6.5 EBSD scan at P91 weld interface (a) IPF map (b) KAM map (d) phase map 117
6.6 EBSD scan at Incoloy 800HT weld interface (a) IPF map (b) KAM map (c) phase map 117
6.7 Prepared tensile specimens and fractured tensile specimens after testing, with engineering stress-strain curves of base metals and tested tensile specimens 118
6.8 Fractography SEM micrographs of (a) AW state standard tensile specimen (b) PWHT state standard tensile specimen (c) AW state subsize tensile specimen (d) PWHT state subsize tensile specimen 119
6.9 2D contour profile plot of microhardness across the specimen in AW and PWHT state 120
6.10 V-notched Charpy impact toughness specimens (a) after fracture (b) fractured tips 121
7.1 Schematics of bead on plate weld sequence employing A-TIG welding 123
7.2 Bead on plate welds: (a) with SiO_2 flux on Incoloy 8000HT plate (b) with TiO_2 flux on Incoloy 8000HT plate (c) with SiO_2 flux on P91 plate (d) with TiO_2 flux on P91 plate 124
7.3 Macrostructure observed for (a-e) with SiO_2 flux on Incoloy 8000HT plate (f-j) with TiO_2 flux on Incoloy 8000HT plate 125
7.4 Macrostructure observed (a-e) with SiO_2 flux on P91 plate (f-j) with TiO_2 flux on P91 plate 125
7.5 (a) A-TIG welding setup; (b) welding process schematic; (c) welded plate; (d) weld macrograph 126
7.6 Detailed visualization of different HAZ regions formed after exposure to different transformation temperatures 127
7.7 Micrographs of (a) AW state WFZ at lower magnification (b) AW state WFZ at higher magnification (c) AW state WFZ under FE-SEM (d) PWHT state WFZ at lower magnification (e) PWHT state WFZ at higher magnification (f) PWHT state WFZ under FE-SEM (g) EDS spectrum of precipitate observed in AW state WFZ (h) EDS spectrum of precipitate observed in PWHT state WFZ 128
7.8 Micrograph of weld interface (a) under an optical microscope (b) in FESEM with line map spectra 129
7.9 Room temperature flat tensile specimens and high temperature (HT) round specimens under tensile loading with the engineering stress-strain curves for the tested specimens 131
7.10 Fractography micrographs of (a) AW state standard specimen (b) PWHT state standard specimen (c) AW state sub-size specimen (d) PWHT state sub-size specimen (e) HT-tensile specimen at 450 ℃ (f) HT-tensile specimen at 550 ℃ 132
7.11 Microhardness variation plot across the P91 WFZ for AW and PWHT specimens 133
7.12 Fractography micrograph of (a) AW state Charpy impact toughness specimen; (b) PWHT state Charpy impact toughness specimen 133
7.13 A-TIG welded plate and weld bead macrograph with stitched optical micrograph of Incoloy 800HT weld 134
7.14 Micrograph of Incoloy 800HT weld interface and line map EDS spectrum across the weld interface 135
7.15 Micrograph of WFZ and area map EDS spectrum over SGB at high magnification 135
7.16 EPMA scan over the Incoloy 800HT weld interface 135
7.17 (a) Engineering stress-strain curve and (b) fractography micrograph of fractured WFZ surface (c) HT-tensile specimen at 550 ℃ (d) HT-tensile specimen at 650 ℃ 136
7.18 Microhardness variation plot across the weld 137
7.19 Macrographs of weld beads observed with (a) no flux (b) NiO (c) CuO (d) SiO_2 (e) TiO_2 (f) MoO_3 (g) Cr_2O_3 (h) V_2O_5 (i) Co_3O_4 (j) multicomponent flux 138
7.20 P91 weld interface (a) stitched optical micrograph (b) FESEM micrograph with line mapping 139
7.21 P91 weld interface (a) IQ map (b) IPF map (c) IQ+grain boundary map (d) KAM map (e) phase map 140
7.22 Incoloy 800HT weld interface FESEM micrograph with line mapping 141
7.23 Incoloy 800HT weld interface (a) IQ map (b) IPF map (c) IQ+grain boundary map (d) KAM map (e) phase map 141
7.24 (a) Equilibrium phase diagram for WFZ (b) Equilibrium calculations and Scheil-Gulliver simulation indicating WFZ solidification microstructure evolution 142
7.25 WFZ (a) Optical micrograph (b) FE-SEM micrograph with EDS 143
7.26 WFZ (a) IQ map (b) IPF map (c) IQ+grain boundary map (d) KAM map (e) phase map 144
7.27 WFZ (a) IPDF plot (b) ODF sections (φ=0˚,45˚, 65˚) 144
7.28 WFZ (a) SGB observed in TEM micrograph with elemental mapping (b) cuboidal precipitate 145

micrograph with SAD pattern and mapping
7.29 Tensile specimen after testing (a) AW standard flat room temperature specimen (b) AW subsize flat room temperature specimen (c) high-temperature (550°C) round tensile specimen (d) high-temperature (650°C) round tensile specimen (e) engineering stress-strain curves for tested tensile specimens 146
7.30 FESEM micrographs (a) AW standard flat room temperature specimen (b) AW subsize flat room temperature specimen (c) high-temperature (550°C) round tensile specimen (d) high-temperature (650°C) round tensile specimen 146
7.31 Contour microhardness variation plot for the P91 and Incoloy 800HT DWJ 147
7.32 (a) Fractured specimen (b) FESEM micrographs of V-notch Charpy impact toughness specimen 148

List of Tables

Table	Title	Page
2.1	Relevant and potential DWJ combinations where grade 22 (2.25Cr-1 Mo) and Grade 91 (9Cr-1 Mo-VNbN) failure was observed in a power plant (Mayr et al., 2019)	5
3.1	Base metal composition (%wt.)	20
3.2	Filler metal composition (%wt.)	20
3.3	Base metal mechanical properties	21
3.4	Laser beam welding process parameters	22
3.5	Electron beam welding process parameters	22
3.6	SMAW welding process parameters while using ENiCrCoMo-1 electrode	22
3.7	M-TIG welding process parameters while using AWSER90S–B9 filler	23
3.8	M-TIG welding process parameters while using ERNiCr-3 filler	23
3.9	M-TIG welding process parameters while using ERNiCrMo-3 filler	23
3.10	M-TIG welding process parameters while using ERNiCrCoMo-1 filler	23
3.11	Autogenous-TIG welding process parameters (involving interlayers)	24
3.12	Buttering technique welding process parameters while using ERNICr-3 filler for buttering layer deposition and ERNiCrCoMo-1 filler for welding	24
3.13	A-TIG welding process parameters	25
4.1	Tensile test results	38
4.2	Fracture locations for the tensile tested specimen in different conditions	39
4.3	Charpy Impact toughness obtained in Charpy impact toughness testing	41
4.4	Segregation coefficient and elemental composition of different structures investigated in the WFZ	48
4.5	Tensile properties of different weld specimens	51
4.6	Tensile properties of different weld specimens	59
5.1	Tensile properties observed for different specimens	67
5.2	Tensile properties for different weld specimens	76
5.3	Tensile properties for different weld specimens	83
5.4	EDS spectra for positions observed in Figure 5.37	87
5.5	EDS spectra for positions observed in Figure 5.38	87
5.6	EDS spectra for positions observed in Figure 5.40	89
5.7	EDS spectra for positions observed in Figure 5.47	94
5.8	Tensile properties for different weld specimens	96
5.9	Tensile properties observed for different specimens	110
6.1	Segregation coefficient and elemental composition of different structures investigated in the WFZ	115
6.2	Tensile properties of different weld specimens	119
7.1	Weld bead width and depth of penetration of different weld beads obtained	125
7.2	Tensile properties	131
7.3	Tensile properties	137
7.4	Tensile strength observed for different specimens	147

List of Symbols

Symbol	*Description*
Al	Aluminum
V	Arc voltage
γ	Austenite
s	Average travel speed
C	Carbon
Cr	Chromium
Co	Cobalt
Cu	Copper
°C	Degree Celsius
δ	Ferrite
Q	Heat input
η	Heat transfer efficiency
g	gram
h	hour
Fe	Iron
Ac1	Lower critical temperature
Mn	Manganese
α	Martensite
Mo	Molybdenum
Ni	Nickel
Nb	Niobium
O	Oxygen
S	Sulphur
Ti	Titanium
W	Tungsten
Ac3	Upper critical temperature
V	Vanadium
HV	Vickers hardness
I	Welding current

List of Abbreviations

Abbreviation	*Full form*
A	Amperes
AISI	American iron and steel institute
ASME	American society of mechanical engineers
ASS	Austenitic stainless steel
ASTM	American society for testing and materials
ATP	Austenite transform products
AUSC	Advanced ultra-supercritical
AW	As-welded
BCC	Body centered cubic
BL	Buttering layer
BM	Base metal
CDZ	Carbon deduced zone
CGHAZ	Coarse heat affected zone
Cr_{eq}	Chromium equivalent
CSEF/M	Creep strength enhanced ferritic/martensite
CTE	Co-efficient of thermal expansion
DCEN	Direct current electrode negative
DHD	Deep hole drilling
DOP	Depth of penetration
DWJ	Dissimilar weld joint
DWR	Depth-to-width ratio
EBSD	Electron backscatter diffraction microscopy
EBW	Electron beam welding
EDS	Energy Dispersive Spectroscopy
EPMA	Electron probe micro analysis
EPMA	Electron probe micro-analyzer
FCC	Face centered cubic
FESEM	Field Emission Scanning Electron Microscopy
FGHAZ	Fine grain heat affected zone
FSTIG	Flux-bounded tungsten inert gas
GOS	Grain orientation spread
GTAW	Gas tungsten arc welding
HAGB	High angle grain boundary
HAZ	Heat affected zone
HT	High temperature
HV	Vickers microhardness
ICHAZ	Intercritical heat affected zone
IPDF	Inverse pole density function
IQ	Image quality
IR	Infra red
l/min	liter per minute
LAFM	Low Activation Ferritic–Martensitic
LAGB	Low angle grain boundary
LBW	Laser welding
LOM	Light optical microscope
MAGB	Medium angle grain boundary
mm	Millimeter
NAPCC	National Action Plan for Climate Change
Ni_{eq}	Nickel Equivalent
ODF	Orientation distribution function
OES	Optical emission spectroscopy
PAG	Prior austenite grain
PAGB	Prior austenite grain boundary
PMZ	Partially mixed zone

PWHT	Post weld heat treatment
RAFM	Reduced Activation Ferritic–Martensitic
RT	Room temperature
SEM	Scanning Electron Microscopy
SMAW	Shielded metal arc welding
TEM	Transmission electron microscopy
TIG	Tungsten arc welding
TRIP	Transformation induced plasticity
TWI	The Welding Institute
TZ	Transition zone
UTM	Universal testing machine
UTS	Ultimate tensile strength
UZ	Unmixed zone
W	Watt
WDS	Wavelength dispersive spectrometers
YS	Yield strength