

Contents

Acknowledgements		I
Table of Contents		II
List of Figures		V
List of Tables		IX
List of Abbreviations and Symbols		XI
Abstract		XII
Chapter 1	Introduction	1
Chapter 2	Literature Review	4
2.	General	4
2.1	Types of Stainless Steels	4
2.1.1	Ferritic Stainless Steels	4
2.1.2	Martensitic Stainless Steels	5
2.1.3	Precipitation Hardening Stainless Steels	5
2.1.4	Austenitic Stainless Steels	5
2.1.5	Duplex Stainless Steels	6
2.2	Austenitic Stainless Steels	9
2.2.1	Heating of Austenitic Stainless Steels	9
2.2.2	Phases in Austenitic Stainless Steels	9
2.2.3	Effect of Annealing of 316L Stainless Steel on Properties	11
2.3	Duplex Stainless Steel	13
2.3.1	Types of Duplex Stainless Steel and Chemical Composition	13
2.3.2	Commercial Grades	13
2.3.3	Heating of Duplex Stainless Steels	14
2.3.4	Phases of Duplex Stainless Steel	15
2.3.4.1	Sigma Stability	15
2.3.4.1.1	Factors Affecting the Formation of Sigma Phase	18
2.3.4.2	Precipitation of the χ Phase	18
2.3.4.3	Precipitation of Nitrides (Cr_2N , CrN)	19
2.3.4.4	Secondary Austenite (γ_2)	20
2.3.4.5	Precipitation of R-Phase	22
2.3.4.6	Precipitation of π -Phase	22
2.3.4.7	Precipitation of ε -Phase	22
2.3.4.8	Precipitation of G-Phase	23
2.3.4.9	Precipitation of Laves-Phase	23
2.4	Welding of Austenitic and Duplex Stainless Steels	24

2.4.1	Welding Technologies	24
2.5	Measuring of Ferrite Number	27
2.5.1	Ferrite Control in Duplex Stainless Steel Weld metal	30
2.6	Effect of Alloying Element of Duplex Stainless Steels	30
2.6.1	Effect of Si & Mn	30
2.6.2	Effect of N	31
2.6.3	Effect of W	32
2.6.4	Effect of Mo	33
2.7	Phase transformations induced p\by heating and welding	34
2.7.1	Embrittlement of Duplex Stainless Steel in Range of 475-1000°C	34
2.7.2	Austenite Reformation in the Heat-Affected Zone of Duplex Stainless Steel 2205	35
2.7.3	Ferrite/Austenite Transformations in the Heat Affected Zone of 2205 Duplex Stainless Steel	36
2.7.4	Microstructural Characterization of Simulated Heat Affected Zone in 2205 Duplex Stainless Steel	38
2.7.5	Microstructure Changes in Fe-24Cr-3Mo-0.14N Duplex Stainless Steel	39
2.8	Corrosion Characteristics of DSS	40
2.8.1	Pitting Resistance Equivalent Number	40
2.8.2	Microstructure and Pitting Corrosion Resistance of Annealed Duplex Stainless Steel	43
2.8.3	Pitting and Galvanic Corrosion Behavior of Laser Welded Stainless Steels	44
2.8.4	Hydrogen Induced Cracking in 2205 Duplex Stainless Steel in wet H ₂ S Environments After Isothermal Treatment	45
2.8.5	Pitting Corrosion Behavior of Large Area Laser Surface Treated 304L Stainless Steel	46
2.8.9	Corrosion Behavior of Sensitized DSS	47
2.9	Performance of Additives in PWRs	51
Chapter 3	Experimental Work	57
3.1	Introduction	57
3.2	Materials	58
3.3	Specimen Preparation and Testing	58
3.3.1	Specimens Welding Processes	58
3.3.1.1	X -Ray Radiography	59
3.3.2	Metallographic Examination	60

3.3.3	Heating	60
3.4	Measurement of Ferrite Content	61
3.5	Mechanical Testing	61
3.5.1	Impact Tests	61
3.5.2	Microhardness Tests	62
3.6	Corrosion Tests	62
Chapter 4	Results and Discussions	66
4.1	Study of Microstructure	66
4.1.1	304L	66
4.1.2	316L	66
4.1.3	Duplex Stainless steel	67
4.2	EDX Analysis	81
4.3	Analysis of Ferrite Content	83
4.3.1	304L	83
4.3.2	316L	84
4.3.3	Duplex Stainless Steel	85
4.4	Microhardness Study	91
4.4.1	304L	91
4.4.2	316L	91
4.4.3	Duplex Stainless Steel	92
4.5	Evaluation of Impact Toughness	98
4.5.1	304L	98
4.5.2	316L	98
4.5.3	Duplex Stainless Steel	100
4.6	Fracture Surface Morphology	104
4.6.1	304L	104
4.6.2	316L	104
4.6.3	Duplex Stainless Steel	105
4.7	Impact Toughness at Low Temperature	119
4.8	Corrosion Characteristics	128
Chapter 5	Conclusions	139
References		141

List of Figures

Fig. 2.1	The Fe-Cr Phase Diagram	10
Fig. 2.2	Schematic TTT diagram showing precipitation of sigma, alpha prime, and other phases in duplex stainless steel	17
Fig. 2.3	Ferrite constitution diagram developed by (a)Schaeffler and (b)Delong diagram showing ferrite content and ferrite number (FN), respectively, as a function of Cr-vs Ni-equivalents	28
Fig. 2.4	The Siewert, Mc Cowan, Olson constitution diagram (1988) for stainless steel	29
Fig. 2.5	Ferrite constitution diagram developed by the WRC in (1992)	29
Fig. 2.6	Schematic TTT diagram for duplex stainless steels with different alloying degrees	34
Fig. 2.7	Vickers micro-hardness indentations on δ and γ phases in the samples aged at 475°C for (a) 4 h (b) 8 h (c) 64 h	42
Fig. 2.8	Effect of aging treatments on Vickers microhardness of δ ferrite and austenite for the aging temperatures 475 and 500°C	43
Fig. 2.9	Potentiodynamic polarization curves of the as-received stainless steels and their corresponding weldments: (a)S30400 (b)S31603 (c) S31803 and (d) S32760 in 3.5% NaCl solution	45
Fig. 2.10	Microstructure of 2205 duplex stainless steel	47
Fig. 2.11	Microstructure of 316L austenitic stainless steel	48
Fig. 2.12	Polarization curves of 2205 stainless steel	49
Fig. 2.13	Polarization curves of 316L stainless steel	49
Fig. 2.14	Relationship between calculated corrosion rate sensitization temperature	50
Fig. 2.15	Relationship between calculated corrosion rate sensitization temperature	50
Fig. 2.16	Relationship between Vickers microhardness and sensitization temperatures	51
Fig. 3.1	Dimensions of single V-grooved joints	64
Fig. 3.2	Welded plate with two specimens rejected from each side	64
Fig. 3.3	Impact test specimen	65
Fig. 3.4	Schematic load-time curve for an instrumented Charpy –test	65
Fig. 3.5	Simulated experimental polarization curve of correlated electrode showing E_{corr} and I_{corr}	66
Fig. 4.1	Microstructure of (304L) base metal after different aging	69

	temperatures (a) as received condition (b) after aging at 650°C (c) after aging at 750°C (d) after aging at 850°C	
Fig. 4.2	Microstructure of 304L weld metal for the as welded condition: (a) 304L(SMAW) (b) 304L (TIG)	70
Fig. 4.3	Microstructure of 304L weld metal (SMAW) after different aging temperatures (a) after aging at 650°C (b) after aging at 750°C (c) after aging at 850°C	70
Fig. 4.4	Microstructure of 304L weld metal (TIG) after different aging temperatures (a) after aging at 650°C (b) after aging at 750°C (c) after aging at 850°C	71
Fig. 4.5	Microstructure of (316L) base metal after different aging temperatures (a) as received condition (b) after aging at 650°C (c) after aging at 750°C (d) after aging at 850°C	72
Fig. 4.6	Microstructure of 316L weld metals (SMAW), (TIG) for as welded and after heating (TIG): (a) as welded (SMAW) ((b) as welded (TIG) (c) after aging at 650°C (d) after aging at 750°C (e) after aging at 850°C	73
Fig. 4.7	Microstructure of 316L weld metal (SMAW) after aging at different temperatures (a) after aging at 650°C (b) after aging at 750°C (c) after aging at 850°C	74
Fig. 4.8	Microstructure of 316L weld metal after heating (TIG) and (SMAW) at 850°C (σ white, γ yellow and α dark brown)	75
Fig. 4.9	Microstructure of DSS base metal (a) as received condition (b) after aging at 475°C (c) after aging at 650°C (d) after aging at 750°C	76
Fig. 4.10	Microstructure of DSS base metal after heating (a) after aging at 750°C (b) after aging at 850°C (Color etching $K_2S_2O_5$)	77
Fig. 4.11	Microstructure of DSS of weld metal for the as welded and after heating (SMAW) and (TIG) (a) as welded (SMAW) (b) as welded (TIG) (c) after aging at 475°C (SMAW) (d) after aging at 475°C (TIG) (e) after aging at 650°C (SMAW) (f) after aging at 650°C (TIG)	78
Fig. 4.12	Microstructure of DSS weld metals after heating (SMAW) and (TIG) at 850°C	79
Fig. 4.13	Microstructure of DSS weld metals after heating (TIG) and (SMAW) after aging at 750 and 850°C (σ white, γ yellow and α dark brown)	80
Fig. 4.14	SEM of DSS base metal after aging at 750 and 850°C (a,b) and WM microstructure for (TIG) after aging at 850°C (c)	82
Fig. 4.15	Effect of aging temperature on the ferrite content of austenitic stainless steel weldments (304L/E308L): (a) TIG and (b) SMAW Welding	88

Fig. 4.16	Effect of aging temperature on the ferrite content of austenitic stainless steel weldments (316L/E316L): (a) TIG and (b) SMAW welding	89
Fig. 4.17	Effect of aging temperature on the ferrite content of duplex stainless steel weldments: (a) TIG and (b) SMAW welding	90
Fig. 4.18	Effect of aging temperature on the microhardness of 304L stainless steel (SMAW) weldment	95
Fig. 4.19	Effect of aging temperature on the microhardness of 304L stainless steel (TIG) weldment	95
Fig. 4.20	Effect of aging temperature on the microhardness of 316L stainless steel (SMAW) weldment	96
Fig. 4.21	Effect of aging temperature on the microhardness of 316L stainless steel (TIG) weldment	96
Fig. 4.22	Effect of aging temperature on the microhardness of SMAW duplex stainless steel weldment	97
Fig. 4.23	Effect of aging temperature on the microhardness of TIG duplex stainless steel weldment	97
Fig. 4.24	Relationship between impact energy and aging temperature for the investigated material: (a) Base metals (b) weld metals (SMAW) (c) weld metals (TIG)	103
Fig. 4.25	SEM fractograph of impact specimen of type 304L (a) as received condition (BM) (b) after aging at 850°C (BM) (c) as welded (SMAW) (d) after aging at 850 °C (SMAW)	107
Fig. 4.26	SEM fractograph of impact specimen of type 304L (TIG) (a) as received condition (b) after aging at 850°C	108
Fig. 4.27	Load – time traces for 304L base and weld metals	109
Fig. 4.28	SEM fractograph of impact specimen of type 316L base and weld metal (SMAW) and TIG weld metals: (a) as received (b) after aging at 850°C (BM) (c) as welded (SMAW) (d) after aging at 850°C (SMAW) (e) as welded (TIG) (f) after aging at 850°C WM (TIG)	111
Fig. 4.29	Load – time traces for 316L base and weld metals	112
Fig. 4.30	SEM fractograph of Impact Specimen of Type DSS (BM): (a) as received condition (b) after aging at 475°C	113
Fig. 4.31	SEM fractograph of impact specimen of type DSS (BM): (a) after aging at 750°C (b) after aging at 850°C	114
Fig. 4.32	SEM fractograph of Impact Specimen of Type DSS (SMAW): (a) as welded condition (b) after aging at 475°C	115
Fig. 4.33	SEM fractograph of Impact Specimen of Type DSS (SMAW): (a) after aging at 650°C (b) after aging at 850°C	116
Fig. 4.34	SEM fractograph of Impact Specimen of Type DSS (TIG): (a) as welded condition (b) after aging at 475°C (c) after aging at 850°C	117

Fig. 4.35	Load – time traces for DSS base and weld metals	118
Fig. 4.36	Relationship between the impact energy and test temperature of investigated materials	125
Fig. 4.37	Fracture surface of investigated materials tested at -196 °C	126
Fig. 4.38	Instrumented impact test load-time traces of investigated materials tested at -196 °C	127
Fig.4.39	Corrosion characteristics of 304L base metal and after heat treatment in 2400 ppm boric acid and solution containing 4ppm LiOH (1a) base metal (1b) after aging at 650°C (1c) after aging at 750°C (1d) after aging at 850°C	132
Fig. 4.40	Corrosion characteristics of 316L base metal and after heat treatment in 2400 ppm boric acid and solution containing 4ppm LiOH (2a) base metal (2b) after aging at 650°C (2c) after aging at 750°C (2d) after aging at 850°C	133
Fig.4.41	Corrosion characteristics of DSS base metal and after heat treatment in 2400ppm boric acid and solution containing 4ppm LiOH (3a) base metal (3b) after aging at 650°C (3c) after aging at 750°C (3d) after aging at 850°C	134
Fig.4.42	Corrosion characteristics of welded by (SMAW) and (TIG) in 2400ppm boric acid and solution containing 4ppm LiOH	135
Fig. 4.43	Corrosion characteristics of welded by (SMAW) and (TIG) in 1% NaCl	136
Fig.4.44	Corrosion surface morphology of weld metal of 304L in 1% NaCl	137
Fig.4.45	Corrosion surface morphology of weld metal of DSS in 1% NaCl	138

List of Tables

Table 2.1	Composition of AISI type 400 ferritic stainless steel	7
Table 2.2	Composition of AISI type 400 martensitic stainless steel	8
Table 2.3	Composition of A ISI type 300 austenitic stainless steel	8
Table 2.4	Chemical compositions (wt %) of most common wrought Duplex stainless steels	14
Table 2.5	Filler metal recommended for commonly used austenitic chromium-nickel steels	25
Table 2.6	Welding consumables of some types of duplex stainless steels	27
Table 3.1	Chemical analysis of (304L stainless steel)	58
Table 3.2	Chemical analysis of (316L stainless steel)	58
Table 3.3	Chemical analysis of (duplex stainless steel)	58
Table 3.4	Chemical analysis of AWS E308L-17	59
Table 3.5	Chemical analysis of AWS E316L-17	59
Table 3.6	Chemical analysis of AWS ER308LSi-17	60
Table 3.7	Chemical analysis of AWS ER316L-17	60
Table 3.8	Chemical analysis of E2209-17	60
Table 3.9	Chemical analysis of ER2209-17	60
Table 4.1	Analysis of precipitations of DSS base and weld metal at 850°C (Microstructure)	83
Table 4.2	Effect of aging temperature on the ferrite content of austenitic stainless steel weldments (304L/E308L) for TIG and SMAW welding processes	87
Table 4.3	Effect of aging temperature on the ferrite content of austenitic stainless steel weldments (316L/E316L) for TIG and SMAW welding processes	87
Table 4.4	Effect of aging temperature on the ferrite content of duplex stainless steel weldments for TIG and SMAW welding processes	87
Table 4.5	Effect of aging temperature on the microhardness (VHN) of 304L stainless steel (SMAW) weldment	93
Table 4.6	Effect of aging temperature on the microhardness (VHN) of 304L stainless steel (TIG) weldment	93
Table 4.7	Effect of aging temperature on the microhardness (VHN) of 316L stainless steel (SMAW) weldment	93
Table 4.8	Effect of aging temperature on the microhardness (VHN) of 316L stainless steel (TIG) weldment	93
Table 4.9	Effect of aging temperature on the microhardness (VHN) of SMAW duplex stainless steel weldment	94
Table 4.10	Effect of aging temperature on the microhardness (VHN) of	94

	TIG duplex stainless steel weldment	
Table 4.11	Effect of aging temperature on impact energy of investigation materials	102
Table 4.12	Effect of test temperature on impact properties of investigated materials	124
Table 4.13	Effect of heat treatment on corrosion rate of stainless steels (BM)	134
Table 4.14	Effect of welding techniques on corrosion rate of stainless steel weld joints in case of as weld conditions	137

List of Abbreviations and Symbols

DSS	Duplex Stainless Steel
WM	Weld metal
HAZ	Heat Affected Zone
BM	Base Metal
PREN	Pitting Resistance Equivalent Number
TEM	Transmission Electron Microscope
EDX	Energy Dispersive X-Ray Analysis
α	Ferrite Phase
γ	Austenite Phase
σ	Sigma Phase
δ	Delta Ferrite
Cr ₂ N, CrN	Chromium Nitrides
χ	Chi- Phase (Cr-Mo-Fe rich phase)
γ_2	Secondary Austenite
M ₂₃ C ₆	Chromium Carbides
R	Precipitation of R-Phase (Si-Mo rich phase)
π	Precipitation of π -Phase
ε	Precipitation of ε -Phase (Epsilon phase)
G	Precipitation of G-Phase (Secondary phase)
ζ	Precipitation of Laves-Phase
α'	Secondary Phase (Alpha Prime)
Fe	Ferrite Content
SMAW	Shielded Metal Arc Welding
TIG (GTAW)	Gas Tungsten Arc Welding
MIG (GMAW)	Gas Metal Arc Welding
FCW	Flux-Cored Arc Welding
PAW	Plasma Arc Welding
PWR	Pressurized Water Reactor
ppm	Part Per Million
SCE	Saturated Calomel Electrode
LBW	Laser Beam Welding
PAW	Plasma Arc Welding
SCC	Stress Corrosion Cracking
PWSCC	Primary Water Stress Corrosion Cracking
VHN	Vickers Hardness Number