Declaration

I hereby declare that the work presented in this Thesis titled "**Experimental investigation on pipeline steel welds fabricated using formulated SMAW electrode coatings**", submitted to the Indian Institute of Technology Jodhpur in partial fulfilment 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 Prof. Rahul Chhibber. The contents of this thesis in full 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.

Aditya Kumar
(P19ME011)

Certificate

This is to certify that the thesis titled "**Experimental investigation on pipeline steel welds fabricated using formulated SMAW electrode coatings**", submitted by Aditya Kumar (P19ME011) 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 my supervision. To the best of my knowledge, the contents of this report, in full 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.

Prof. Rahul Chhibber
Ph.D. Thesis Supervisor
Indian Institute of Technology, Jodhpur

Abstract

The growing energy demand and advancements in pipeline steel technology necessitate the development of specialized welding consumables. This study examines X70 pipeline steel welds using formulated SMAW electrode coatings, with a focus on consumable performance, weld undermatching, hydrogen effects, and ductile fracture modeling.

The flux formulation was targeted for high basicity, lower silica and rutile, substitution of CaO with BaO, low hydrogen (high CaF_2). Four major constituents were selected for investigation, $CaF_2 - CaO - Al_2O_3 - BaO$ and $CaO - SiO_2 - CaF_2 - BaO$. Extreme vertices design approach was used for experimental design. The flux was investigated for contact angle, work of adhesion, and floatation coefficient, weight loss %, enthalpy change, thermal diffusivity, thermal conductivity, specific heat. Neural network models were developed for enhanced prediction accuracy. Increasing CaO and BaO raises the work of adhesion and lowers the flotation coefficient, while increasing Al_2O_3 and CaF_2 decreases the work of adhesion and raises the flotation coefficient. The structural analysis of as-quenched slag was done by XRD, UV-vis, and FTIR. The CaO and BaO act as network breakers and release non-bridging oxygen O^- at the expense of bridging oxygen O^0. The contact angle decreases with the increase of CaO and BaO. The increase in individual constituents Al_2O_3 and CaF_2 increases the contact angle. The Al_2O_3 act as a network former in the melts. The CaF_2 present in the melt as Ca^{2+} and F^- due to higher CaF_2 concentration (~35%) which has positively affected the contact angle.

An increase in CaF_2 exhibits better thermal stability compared to the other minerals used. An increase in CaO and BaO has positive an influence, comparatively, BaO has more thermal stability. The primary cause of weight loss is due to moisture, crystallization water, calcination, and other volatile compounds present in the mineral. The thermal stability of flux while heating results in lower gaseous infiltration in the molten weld pool. Increasing alumina enhances thermal diffusivity, while an increase in calcite lowers thermal diffusivity. The solubility of water vapor in molten slag was estimated to range from 3.095 to 3.546.

A series of multi-pass bead-on-plate studies were conducted using laboratory-developed electrodes. The flux composition has shown a significant effect on all the responses. An increase in Al_2O_3, and BaO has shown a positive influence on nickel transfer, whereas an increase in CaO reduces nickel transfer. The slag detachability was found to be good for the ratio CaF_2: CaO: Al_2O_3:: 1.76:0.73:0.51.

Selection of better-performing electrode coatings was done. Two weldments were prepared using developed welding electrodes (AF_W, SF_W), and one using a commercial electrode E8018-G (CE_W) for comparison purposes. The mechanical, metallurgical, and hydrogen charging tests were performed. Even with the same electrode rod (ER80S-Ni1), both coating compositions have shown significant effects on the weld. The AF_W and SF_W welds have shown thin grain boundaries and acicular ferrite as compared to CE_W. The results were confirmed by a thermodynamic model that shows a reduction in ferrite and pearlite. Microhardness results are in agreement with phase fraction microhardness results. Due to fine ferrite morphologies, lower hydrogen embrittlement index for AF_W was achieved. Weld strength mismatch in decreasing order is SF_W, AF_W, and CE_W. The σ_{YS}/σ_{UTS} ratio of weld AF_W was better than the other welds.

Uniaxial tensile tests and single edge notch bend tests with $a_o/W = 0.50$ and $a_o/W = 0.25$ in-plane constraints were tested for X70 steel and weld (AF_W). The single edge notch bend pre-crack was prepared using electric-discharge machining. The test results of $a_o/W = 0.50$ were used to calibrate the GTN parameters using the design of experiment. The GTN model parameters were validated on $a_o/W = 0.25$ and flat notch tensile test experiments. The GTN model parameters were also validated on notch round bar and single edge notch tension test. The weld inhomogeneity was considered to simulate the pop-in behavior of single-edge notch bend tests. The simulations of single-edge notch bend tests with EDM-cut cracks and sharp cracks were studied, showing that the initial fracture toughness increases for EDM-cut cracks.

Acknowledgements

I am profoundly grateful to *Prof. Rahul Chhibber*, whose outstanding guidance directed my Ph.D. journey. His immense knowledge, and constant encouragement has influenced the trajectory of my research, providing direction, purpose, and academic rigor. His expertise, from problem conceptualization to results analysis, has been crucial, making this journey an intellectually stimulating and fulfilling experience.

I extend my heartfelt gratitude to my Doctoral Committee members, *Dr. Chandan Pandey*, *Dr. Ravi K.R.*, and *Dr. Jaiveer Singh*, for their invaluable support and encouragement that inspired me through various stages of my doctoral program. I would like to thank the IIT Jodhpur Dept. of Mechanical Engineering, the Central Workshop personnel, the Centre for Research & Development of Scientific Instruments (CRDSI) personnel, *Dr. Abir Bhattacharyya, Mr. Aman Verma*, Dept. of Metallurgical and Materials Engineering, *Prof. Ambesh Dixit, Mr. Chandra Prakash* Dept. of Physics. I also extend my thanks to *Dr. Sandip Haldar* and *Dr. Harpreet Singh* from IIT Goa for their contribution to my research journey.

My doctoral journey has been profoundly enriched by my exceptional lab mates, *Dr. Anup, Mr. Vijay, Mr. Alok* and *Mr. Sudish.* Their friendship and support brought joy and comfort to my research journey. I also extend my gratitude to senior lab members, *Dr. Waris Nawaz Khan, Dr. Lochan Sharma*, and *Dr. Sumit Mahajan*, for their guidance. I cherish the memories and support of my friends and colleagues: *Dr. Prince, Dr. Laxmi Kant, Dr. Arvind, Mr. Prasad, Mr. Swarit, Mr. Sunil, Mr. Meraj, Mr. Ankit, Dr. Gaurav, Mr. Nitin, Mr. Chandan*, and *Mr. Pankaj*, who made my time at IIT Jodhpur a truly wonderful experience. I would also like to thank the educators on YouTube and the GitHub community for their advocacy of *knowledge as a human right*.

The unconditional love and support of my parents, *Mr. Gyan Prakash Kushwaha and Mrs. Kusum Kushwaha*, has strengthen me in every step. The suggestions and motivational support from my sister, *Dr. Anamika*, have been very cheering for my Ph.D. journey. Her encouragement, and understanding have been my pillars of strength. I am thankful to my family and my nephew throughout this journey.

My Ph.D. journey has made me able to witness myself more keenly. For every blessing, grace, pleasant, or unpleasant experience I have, एतस्य वा अक्षरस्य प्रशासने, as per the Imperishable rules.

Aditya Kumar
Ph.D. Student

॥अनश्नन्नन्यो अभिचाकशीति॥ श्वे.उ.

Contents

	Page no.
Declaration	*iii*
Certificate	*v*
Abstract	*vii*
Acknowledgements	*ix*
Contents	*xiii*
List of Figures	*xv*
List of Tables	*xix*
List of Symbols	*xxi*
List of Abbreviations	*xxiii*
Chapter: 1 Introduction	**1**
1.1 OVERVIEW	1
1.1.1 Pipeline steels	1
1.1.2 Structural integrity of pipelines	2
1.1.3 Role of flux coating	3
1.2 JUSTIFICATION OF THE CURRENT STUDY	4
1.3 THESIS OUTLINE	5
Chapter: 2 Literature Survey	**7**
2.1 WELDABILITY OF PIPELINE STEELS	7
2.2 FLUX COATINGS CONSTITUENTS AND ITS SIGNIFICANCE	7
2.2.1 The Wettability and structural properties of flux	7
2.2.2 Thermophysical and physicochemical behavior	8
2.3 EFFECT OF FLUX ON WELD PROPERTIES	9
2.4 EFFECT OF HYDROGEN ON WELD	11
2.5 FRACTURE MECHANICS AND FINITE ELEMENT ANALYSIS	13
2.5.1 Introduction to pipeline fracture	13
2.5.2 Classification of fracture mechanics	14
2.5.3 J-integral	16
2.5.4 Gurson-Tvergaard-Needleman Model	17
Chapter: 3 Problem Statement	**19**
3.1 RESEARCH GAPS	19
3.2 RESEARCH OBJECTIVES	19
3.3 METHODOLOGY	20
Chapter: 4 Experimentation	**21**
4.1 FLUX FORMULATION AND BEAD-ON-PLATE EXPERIMENTS	21
4.1.1 Design of experiments	21
4.1.2 Flux preparation	24
4.1.3 Wettability tests	25
4.1.4 Thermophysical and physicochemical tests	26
4.1.5 Theoretical estimation of flux coating behavior	27
4.1.6 Structural characterization of flux and slag	28
4.1.7 Bead-on-plate experiments	29
4.1.8 Microhardness, and element transfer tests	29
4.2 SELECTION OF FLUX	30
4.3 MATERIALS AND WELDMENT PREPARATION	33
4.3.1 Microstructural and mechanical tests	34
4.3.2 Cathodic charging of specimens	35
4.4 DUCTILE FRACTURE AND FINITE ELEMENT ANALYSIS	35
4.4.1 Experiments	35
4.4.2 J integral	36
4.4.3 Inverse approach of GTN parameters identification	37
4.4.4 Simulation details	38

Chapter: 5 Results and Discussion **41**
5.1 CHARACTERIZATION OF FLUX COATINGS AND BOP 41
5.1.1 High temperature wettability 41
5.1.2 Thermophysical and physicochemical properties 47
5.1.3 Bead-on-plate experiments 55
5.1.4 Structural properties of flux and slag 64
5.2 CHARACTERIZATION OF THE SELCETED FLUX FOR WELD 67
5.3 CHARACTERIZATION OF WELD 68
5.3.1 Inspection of weld 68
5.3.2 Impact test 69
5.3.3 Microhardness test 71
5.3.4 Tensile test 73
5.3.5 Effect of hydrogen charging 74
5.3.6 Metallurgical test 77
5.4 ANALYSIS OF DUCTILE FRACTURE 86
5.4.1 Material property 86
5.4.2 Regression analysis and parametric study 86
5.4.3 Validation of GTN parameters with experiments 89
5.4.4 Validation on different geometries from literature 91
5.4.5 Effect of crack tip sharpness 92

Chapter: 6 Conclusions and Scope for Future Work **95**
6.1 CONCLUSIONS 95
6.1.1 Ductile fracture modeling 95
6.1.2 Weldment characterization 95
6.1.3 Bead-on-plate investigations 96
6.1.4 High temperature wettability investigations 96
6.1.5 Thermophysical and physicochemical investigations 96
6.2 SCOPE FOR FUTURE WORK 96
References 99
APPENDIX A: SUPPLEMENTARY DETAILS 109
A.1 Regression models and ANOVA tables 109
A.2 Supplementary figures 119
A.3 List of Publications 121

List of Figures

Figure	*Title*	*Page no.*
1.1	(a) Trend of natural gas production in India (b) Crude oil and natural gas production in India	1
1.2	(a) History in line pipe steels (large diameter pipe) (b) Causes of pipeline significant incidents	2
1.3	Methods to address the weld issues	3
2. 1	Schematic representation of the local network structure in the CaO-SIO_2-Al_2O_3-FeO-Fe_2O_3 system's surface layer and bulk phase	8
2.2	Optical microstructure of as-welded zone in the weld metal. (a) E7018G-0, (b) E7018G-0.6, (c) E7018G-0.8, (d) E7018G-1.2, (e) E7018G-1.7	11
2.3	Stress strain curve under different environmental condition (a) (b) (Yadav et al., 2023) (c) (Wang et al., 2022)	12
2.4	Fractography of tensile specimens under different environment	13
2.5	Effect of fracture specimen geometry on fracture toughness	13
2.6	stress near the crack tip in an elastic material	15
2. 7	Mode I, mode II, and mode III type of deformation	15
2. 8	Plane stress and plane strain zone along the thickness	16
2.9	Arbitrary J integral contour path around the crack surface	16
2.1	(a) Schematic of ductile crack growth (b) computational cell model	18
4.1	AF flux (a) Quaternary plot projections of composition range (AF flux) (b) Space diagram of treatment combinations	23
4.2	SF flux (a) Quaternary plot projections of composition range (b) Space diagram of treatment combinations	24
4.3	Schematic representation of (a) pellet dimensions (mm) and melting of pellets on the substrate (b) surface tension, contact angle, and spread area of the molten pellet (c) measurement of contact angle.	26
4.4	(a) schematic of hot disk analysis (b) schematic of SMAW electrode, direction of heat flow and thermal constants.	27
4.5	(a) welding setup and developed electrode (b) Schematic of slag metal reactions (c) weld bead using developed electrode (d) schematic for specimens' extraction	30
4.6	Microhardness measurement of the specimens A22	30
4.7	(a) schematic of SMAW and plate dimensions, (b) Welded plates, (c) Multi-pass weld and specimen dimension, (d) Impact specimen dimension, (e) Cathodic charging	34
4.8	(a) Dimensions of flat tensile specimens, (b) Schematic of SENB specimen (c) EDM cut crack and SENB specimens, (d) Experimental test setup for SENB (e) CMOD measurement using DIC	36
4.9	(a) Quarter symmetric 3-D simulation model of tensile bar, (b) SENB a0/W=0.50 2-D simulation meshing (c) Schematic of the effect of reheated zone on multi-pass weld (d) Modified fracture process zone	39
4.10	Meshing followed by SENB with EDM cut crack and sharp crack.	40
5.1	Comparison of regression analysis (RA) prediction and ANN prediction with actual results (a) contact angle (b) spread area (c) work of adhesion (d) floatation coefficient	43
5.2	Trace plot of the regression model of (a) contact angle (b) work of adhesion (c) floatation coefficient	46
5.3	The contour plots of the wetting properties θ, As, Wa and Δ	47
5.4	(a) (b) TGA curve of the coating fluxes AF9 and AF25, (c) (d) DSC curves of the coating fluxes AF13 and AF17	48
5.5	(a) Structure of ANN model; comparison of ANN and RA prediction from actual values (b) weight loss, (c) enthalpy, (d) thermal diffusivity, (e) thermal conductivity, (f) specific heat	51
5.6	Trace plots of the regression model (a) WL, (b) ΔH, (c) λ, (d) α, (e) Cp	54
5.7	Contour plots of the regression model WL, ΔH, λ, α, Cp	55
5.8	Comparison of ANN and regression prediction on unseen test data (a) δNi, (b) δMo, (c) δMn, (d) MH	58

5.9	Trace plot showing response variation with the deviation from reference blend (CaF_2=33.25, CaO=16.75, Al_2O_3=13.25, and BaO=6.75) (a) δNi, (b) δMo, (c) δMn, (d) MH	60
5.10	Contour plots showing response variation δNi, δMo, δMn, MH	61
5.11	Visual inspection of bead on plate specimens	62
5.12	(a) Slag metal inclusion reactions (Deng et al., 2020) (b) Microstructure of the weld specimens A9 at low magnification, Microstructure of the weld specimens at high magnification (c) A3, (d) A9, (d) A13, (f) A25.	63
5.13	EDS and area mapping of specimens A25	64
5.14	Microstructure evolution mechanism in low alloy steel welds	64
5.15	(a) XRD pattern of AF flux (b) FTIR spectra of AF flux	65
5.16	XRD pattern of as-quenched slag	65
5.17	(a) FTIR spectra of as-quenched slag (AF) (b) UV-vis spectra of as-quenched slag (AF)	66
5.18	(a) FTIR spectra of as-quenched slag (SF) (b) UV-vis spectra of as-quenched slag (SF)	67
5. 19	Effect of CaF2 addition to the silicate	67
5.20	(a) Prepared welds, (b) Dye penetrant test, (c) Weld surface with developer (d) Specimens from weld cross section for metallurgical tests	69
5.21	Average Charpy impact energy of X70 and weld	70
5.22	SEM fractography of (a, b) X70, (c, d) AF_W, (e, f) SF_W, (g, h) CE_W	70
5.23	(a) Average microhardness of weld from cap to root, (b) Microhardness vs cooling rate prediction from the chemical composition	71
5.24	Microhardness variation from weld centerline to HAZ (a) Fill pass, (b) Cap pass	72
5.25	Hardness diagram showing BM, HAZ, and weld components, along with terms for strength imbalance	73
5.26	(a) Engineering stress-strain curves of X70, AF_W, SF_W, and CE_W (b) Rupture location of tensile specimens	74
5.27	(a) Schematic of hydrogen charging, (b) appearance of charged specimens, (c) SEM micrograph of charged X70.	74
5.28	Microhardness of with (-ch) and without hydrogen charging of X70, AF_W, SF_W, and CE_W	75
5.29	(a-d) Tensile stress strain curves of base and weld metal with (--ch) and without hydrogen charging	75
5.30	Fractography appearance of ruptured tensile specimen with (-ch) and without hydrogen charging (a) X70 (b) AF_W (c) SF_W (d) CE_W	77
5.31	Optical micrograph of (a, b) X70 base metal, (c, d) weld AF_W, (e, f) weld SF_W, (g, h) CE_W	78
5.32	Phase transformation sequence for low alloy steel welds	78
5.33	(a) Schematic of different weld zones in multi-pass weld, (b) optical micrograph showing weld and HAZ, (c) image analysis showing different zones in weldment.	79
5.34	SEM images of (a) X70, (b) AF_W, (c) SF_W, (d) CE_W	80
5.35	EBSD analysis of weldment (a) IPF maps, (b) grain orientation maps, (c) grain size measurement, (b) Total number fraction of HAGB and LAGB, (e) grain boundary map base metal, (f) grain boundary map weld, Pole figures and IPF texture (g) base metal, (h) weld metal, (i) HAZ	82
5.36	(a) Comparison of CCT curve (b) TTT curves using MUCG83 model, (c) equilibrium phase diagram of X70 and weld (MatSQ FE 2.0)	84
5.37	EDS investigation of the inclusions present in weld (a) AF_W, (b) SF_W	85
5.38	Comparison of non-metallic inclusion sizes present in weld and base (a) AF_W, (b) SF_W (c) CE_W, (d) X70	85
5.39	True stress vs. true plastic strain curve for BM and WM	86
5.40	A 2-dimensional plane strain analysis with CPE4R element and failed element with void volume fraction reaches final void volume fraction.	87
5.41	Contour plots and perturbation plots of (a)Obj_1 (b) Obj_2, (c) Obj_3	88
5.42	Effect of mesh size on BM SENB a_o/W=0.50 (a) Load vs. CMOD curves (b) CMOD vs.Δa_{un}	88
5.43	(a) Triaxiality of flat tensile and flat notch tensile specimen (b) Fractography showing the effect of triaxiality. Comparison of experimental and simulated tensile load-displacement (c, d) BM and WM	89

5.44 Comparison of experimental and simulated results of SENB, (a) Load-CMOD curve, (b) Load-Δa_{un} curve, (c) CMOD-Δa_{un} curve, (d) J-Δa curve of BM 90
5.45 Comparison of experimental, GTN + Mod_FPZ, and GTN results of weld SENB, (a) Load-CMOD curve, (b) JQc values for WM SENB 91
5.46 Simulation for the testing of X70 GTN model parameters (a) Axisymmetric model for NRB1 and NRB0.5 tensile test (b) SENT 2-D simulation model meshing and CTOD location. 92
5.47 (a) Validation of GTN model parameters on round notch tensile load displacement results (b) Validation of GTN model parameters on SENT test, Load-CMOD curve, and CTOD- Δa curve 92
5.48 (a) Schematic of J–Δa curve showing blunting, initiation, and propagation of crack, (b) GTN simulation results showing high initial fracture toughness of EDM cut crack as compared to sharp crack front. 93

List of Tables

Table	*Title*	*Page no.*
1.1	Mechanical properties of API PSL1 and PSL2 pipelines	2
1.2	Summary of the report by Joint Industry Project on X70 pipeline weld	4
4.1	Chemical composition of the minerals	22
4.2	Design matrix of the experiments for fluoro-aluminate (AF) type	22
4.3	Design matrix of the experiments for fluoro-silicate (SF) type	23
4.4	Surface tension and optical basicity data for the constituents	28
4.5	Visual observation prepared during welds using AF flux	31
4.6	Visual observation prepared during welds using SF flux	32
4.7	Final flux composition	32
4.8	XRF result of E8018-G coating	33
4.9	Parameters of welding procedure	33
4.10	Design matrix for X70 GTN parameter calibration	38
5.1	Wetting properties and corrected optical basicity of different flux compositions (AF flux)	41
5.2	Wetting properties and corrected optical basicity of different flux compositions (SF flux)	42
5.3	ANN training details for wettability models	43
5.4	Test dataset for AF flux system	44
5.5	Mean absolute percentage error (MAPE) of RA and ANN prediction on the test data set	44
5.6	TGA-DSC and hot disk analysis results (AF flux)	48
5.7	TGA-DSC and hot disk analysis results (SF flux)	49
5.8	ANN training details for thermophysical and physicochemical models	50
5.9	Mean absolute percentage error (MAPE) of RA and ANN prediction on the test data set	50
5.10	Estimation of element transfer and microhardness (AF flux)	55
5.11	Estimation of element transfer and microhardness (SF flux)	56
5.12	ANN training details for element transfer and MH models	57
5.13	Mean absolute percentage error (MAPE) of RA and ANN prediction on the test data set	57
5.14	Coating flux characteristics used for weld AF_W and SF_W	68
5.15	Chemical composition of weld and X70 base metal	68
5.16	Area reduction of the tensile specimen with and without hydrogen charging	76
5.17	Coefficients of regression equation	87
5.18	Calibrated GTN model parameter for X70 and weld	89

List of Symbols

Symbol	*Description*
θ	Contact Angle.
γ_s	Surface Tension Of Slag
W_a	Work Of Adhesion
Δ	Floatation Coefficient
α	Thermal Diffusivity
λ	Thermal Conductivity,
C_P	Specific Heat
ρ	Density
ΔH	Enthalpy
Λ^{corr}	Corrected Optical Basicity
Λ_{new}	New Optical Basicity
δE	Element Transfer
E	Young's Modulus
K	Strength Coefficient
n	Strain Hardening Coefficient
σ_{YS}	Yield Strength
σ_{UTS}	Ultimate Tensile Strength
σ_Y	Effective Yield Strength
σ_e	Effective Von-Mises Stress
σ_M	Tensile Flow Strength
σ_h	Hydrostatic Stress
ε_M^p	Equivalent Plastic Strain
$\dot{\varepsilon}_M^p$	Equivalent Plastic Strain Rate
$\dot{\varepsilon}_{kk}^p$	Volume Dilation Rate
f^*	Modified Void Volume Fraction
f	Current Void Volume Fraction
s_N	Standard Deviation
ε_N	Mean Strain For Void Nucleation
f_c	Critical Void Volume Fraction
f_f	Final Void Volume Fraction
f_o	Initial Void Volume Fraction
f_N	Volume Void Fraction Of Nucleating Voids
q_1,q_2,q_3	Void Interaction Parameter
l_c	Critical Length Parameter
K	Stress Intensity Factor
J	J Integral
J_{el}	Elastic J
J_{pl}	Plastic J
$C_{(i)}$	Compliance
A_{pl}	Plastic Area
W	Width
S	Span
B	Thickness
B_N	Net Thickness
B_e	Effective Thickness
a_o	Initial Crack Length
a_i	Current Crack Length
b_o	Initial Ligament $(W - A_O)$
b_i	Current Ligament $(W - A_I)$
Δa	Crack Propagation $(A_I - A_O)$

List of Abbreviations

Abbreviation	*Full form*
API	American Petroleum Institute
AWS	American Welding Society
ASTM	American Society For Testing And Materials
HSLA	High Strength Low Alloy
EDM	Electric Discharge Machining
LEFM	Linear Elastic Fracture Mechanics
EPFM	Elastic Plastic Fracture Mechanics
ANN	Artificial Neural Network
MSE	Mean Square Error
MAPE	Mean Absolute Percentage Error
ANOVA	Analysis Of Variance
SMAW	Shielded Metal Arc Welding
HAZ	Heat Affected Zone
FGHAZ	Fine Grain Heat Affected Zone
CGHAZ	Coarse Grain Heat Affected Zone
TTT	Time Temperature Transformation
CCT	Continuous Cooling Transformation
MH	Microhardness
BOP	Bead-On-Plate
BI	Basicity Index
DIC	Digital Image Correlation
GTN	Gurson–Tvergaard–Needleman
AF	Fluoro Aluminate Flux
SF	Fluoro Silicate Flux
BM	Base Metal
WM	Weld Metal
SENB	Single Edge Notch Bend
SENT	Single Edge Notch Tensile
CT	Compact Tensile
FPZ	Fracture Process Zone
CMOD	Crack Mouth Opening Displacement
CTOD	Crack Tip Opening Displacement
VVF	Void Volume Fractions
PEEQ	Plastic Strain Equivalent