Influence of welding on high strength steel butt joints

Chen, Cheng

2019

Chen, C. (2019). Influence of welding on high strength steel butt joints. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/104278>

<https://doi.org/10.32657/10356/104278>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**INFLUENCE OF WELDING ON HIGH
STRENGTH STEEL BUTT JOINTS**

**CHEN CHENG
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING**

2019

INFLUENCE OF WELDING ON HIGH STRENGTH STEEL BUTT JOINTS

CHEN CHENG

School of Civil and Environmental Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfilment of the requirement for the degree of
Doctor of Philosophy

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

21/Jan /2019
.....
Date

Chen Cheng
.....
CHEN CHENG

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations are conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

21 Jan 2019
Date

Fung Tat Ching

Authorship Attribution Statement

This thesis contains material from 2 papers published in the following peer-reviewed journal(s) where I am the first and/or corresponding author.

Partial content of chapter 4 and 5 is published as C. Chen, S.P. Chiew, M.S. Zhao, C.K. Lee, T.C. Fung. Welding effect on tensile strength of grade S690Q steel butt joint. *Journal of Constructional Steel Research*, 153 (2019): 153-168.

The contributions of the co-authors are as follows:

- Prof Chiew and Prof Fung provided the initial project direction and edited the manuscript drafts.
- I prepared the manuscript drafts. The manuscript is revised by Prof Lee.
- I co-designed the study with Prof. Chiew, Prof. Lee and Dr. Zhao and performed all the laboratory work at the school of civil and environmental engineering. I also analyzed the data
- All the experiments, including microstructures, micro-hardness and tensile test, are conducted by me in the material lab and constructional technology lab. Prof. Chiew, Prof. Lee and Dr. Zhao provide guidance in the interpretation of experimental results
- The numerical analysis is carried out by me, and Prof. Chiew, Prof. Lee and Dr. Zhao provide guidance in the interpretation of numerical results

Partial content of chapter 4 is submitted as C. Chen, S.P. Chiew, M.S. Zhao, C.K. Lee, T.C. Fung. Experimental study of welding effect on S690Q high strength steel butt joint, *Journal of Constructional Steel Research*, JCSR_2018_1176

The contributions of the co-authors are as follows:

- Prof Chiew and Prof Fung provided the initial project direction and edited the manuscript drafts.
- I prepared the manuscript drafts. The manuscript is revised by Prof Lee.

- I co-designed the study with Prof. Chiew, Prof. Lee and Dr. Zhao and performed all the laboratory work at the school of civil and environmental engineering. I also analyzed the data
- All the experiments, including microstructures, micro-hardness and tensile test, are conducted by me in the material lab and constructional technology lab. Prof. Chiew, Prof. Lee and Dr. Zhao provide guidance in the interpretation of experimental results

21 / Jan / 2019
.....
Date

Chen Cheng
.....
CHEN CHENG

ACKNOWLEDGEMENT

The author would like to express his sincere gratitude to his supervisor, Prof. Fung Tat-Ching, and co-supervisor, Prof. Chiew Sing-Ping, for their patient guidance, constant encouragement and constructive suggestion throughout this research project. Special thanks are also given to Prof. Lee Chi-King for his valuable instruction and assistance during this period.

Great appreciation is given to Dr. Zhao M. S. for his patient guidance and valuable advice. The author would also like to thank Mr. Jin Y. F., Ms. Cai Y. Q., and Mr. Gan B. Z., for their friendship and help.

Finally, the author sincerely thanks his parents for their continuous encouragement, unfailing support and love.

TABLE OF CONTENTS

ACKNOWLEDGEMENT	<i>I</i>
TABLE OF CONCENTS	<i>II</i>
SUMMARY	<i>VI</i>
LIST OF TABLES	<i>VIII</i>
LIST OF FIGURES	<i>X</i>
LIST OF SYMBOLS	<i>XV</i>
CHAPTER 1 INTRODUCTION	<i>1</i>
1.1 Background	<i>1</i>
1.2 Objectives and Scope	<i>3</i>
1.3 Contributions and Originality	<i>5</i>
1.4 Organization	<i>6</i>
CHAPTER 2 LITERATURE REVIEW	<i>8</i>
2.1 High Strength Steel (HSS)	<i>8</i>
2.1.1 Overview	<i>8</i>
2.1.2 Metallurgy of HSS	<i>12</i>
2.1.3 Mechanical properties of HSS at elevated temperatures	<i>16</i>
2.1.4 Mechanical properties of HSS after exposure to high temperatures	<i>19</i>
2.2 Influence of Welding on High Strength Steel	<i>22</i>
2.2.1 Thermal cycle of welding	<i>22</i>
2.2.2 Microstructure in heat affected zone	<i>25</i>
2.2.3 Mechanical performance of heat affected zone	<i>29</i>

2.3	Performance of Welded High Strength Steel Structures	33
2.3.1	<i>Column</i>	33
2.3.2	<i>Beam</i>	37
2.3.3	<i>Joint</i>	38
CHAPTER 3	MATERIAL TEST OF HSS AFTER COOLING FROM HIGH TEMPERATURES WITH DIFFERENT RATES	43
3.1	Introduction	43
3.2	Experimental Study	45
3.2.1	<i>The test setup</i>	45
3.2.2	<i>Test specimen</i>	47
3.2.3	<i>Reliability and consistency of the testing setup and testing procedure</i>	50
3.2.3.1	<u><i>Heat and cooling test</i></u>	50
3.2.3.2	<u><i>Homogeneity test</i></u>	53
3.2.3.3	<u><i>Size of the tensile test coupon</i></u>	56
3.2.3.4	<u><i>Reliability of the test setup</i></u>	58
3.2.4	<i>Test procedure</i>	60
3.3	Test Results	65
3.3.1	<i>Failure mode</i>	65
3.3.2	<i>Stress-strain curves</i>	65
3.3.3	<i>Characteristic strength and reduction factor</i>	70
3.4	Conclusions	74
CHAPTER 4	INFLUENCE OF WELDING ON TENSILE STRENGTH OF HSS BUTT JOINTS	76
4.1	Introduction	76
4.2	Experimental Investigation	78

4.2.1	<i>Material used</i>	78
4.2.2	<i>Joint fabrication</i>	79
4.2.3	<i>Test procedure</i>	91
4.3	Test Results	95
4.3.1	<i>Microstructure of HAZ</i>	95
	4.3.1.1 <u><i>ROT S690 HSS HAZ</i></u>	95
	4.3.1.2 <u><i>TMCP S690 HSS HAZ</i></u>	102
4.3.2	<i>Hardness test results and size of HAZ</i>	105
4.3.3	<i>Tensile performance of HSS butt joint</i>	118
4.4	Conclusions	124
CHAPTER 5	NUMERICAL INVESTIGATION OF WELDING IMPACT ON HSS BUTT JOINTS	126
5.1	Introduction	126
5.2	Thermal Analysis Model	127
	5.2.1 <i>Double ellipsoid heat source</i>	127
	5.2.2 <i>Thermal property definition</i>	129
	5.2.3 <i>Mesh and boundary condition</i>	130
5.3	Stress Analysis Model	131
	5.3.1 <i>Mechanical property definition</i>	131
	5.3.2 <i>Mesh and boundary condition</i>	138
5.4	Simplified Model	140
5.5	Verification of Numerical Model	147
	5.5.1 <i>Welding thermal cycles</i>	147
	5.5.2 <i>Failure mode</i>	153
	5.5.3 <i>Stress-strain curves</i>	155

5.6	Conclusions	161
CHAPTER 6	INFLUENCE OF COOLING RATE ON TENSILE PERFORMANCE OF HSS BUTT JOINTS	163
6.1	Introduction	164
6.2	Numerical Model Information	162
6.3	Numerical Results	166
6.3.1	<i>Failure mode</i>	166
6.3.2	<i>Stress-strain curves</i>	167
6.3.3	<i>Characteristic strength</i>	171
6.4	Cooling Rate Formula	178
6.5	Conclusions	181
CHAPTER 7	CONCLUSIONS AND FUTURE WORK	183
7.1	Introduction	183
7.2	Conclusions	184
7.2.1	<i>Material property of S690 HSS after cooling from high temperature with different rates</i>	184
7.2.2	<i>Welding influence on S690 HSS butt joints</i>	185
7.2.3	<i>Numerical simulation of welding influence on S690 HSS butt joints</i>	186
7.2.4	<i>Influence of cooling rate on tensile behaviour of S690 HSS butt joints</i>	187
7.3	Future Work	187
REFERENCES		189
APPENDIX A		202
APPENDIX B		215

SUMMARY

In this study, the influence of welding on the mechanical behaviour of high strength steel (HSS) butt joints is investigated experimentally and numerically. In order to achieve the intended investigation purposes, the whole study is divided into four parts, including material property study of HSS after cooling from different peak temperatures with different cooling rates, experimental study of welding influence on HSS butt joints, numerical simulation of welding influence and its corresponding verification, and numerical parametric study of cooling rate on tensile behaviour of HSS butt joints.

In the first part of investigation, it is to experimentally explore the mechanical property of S690 HSS after cooling down from different peak temperatures with different cooling rates. A new setup is designed to heat and cool the specimen. Verification test is carried out to make sure the setup could heat and cool the specimen uniformly. The specimens are heated up to 600°C, 700°C, 800°C, 900°C and 950°C, and then cooled down with different rates by blowing air. The test results are explained in terms of stress-strain curves classified by peak temperature and cooling rate and corresponding characteristic strength, including yield strength and tensile strength. The obtained material properties will be employed in numerical simulation to define the mechanical behaviour of HAZ.

In the experimental study of welding influence on S690 HSS butt joint, eleven butt joints are fabricated by using 8 mm, 12 mm, 16 mm and 22 mm thickness plates. Among the plates, 8 mm, 12 mm and 16 mm plates are delivered by reheated, quenched and tempered (RQT) process, and 22 mm plate is fabricated by thermo-mechanically controlled process (TMCP). The adopted welding method in test is shielded Metal Arc Welding (SMAW), and electrodes with different diameter are used to achieve different welding heat inputs. After the joints are fabricated, coupons are carefully cut out from the welded joints. Tensile tests are then conducted to investigate the impacts of welding on the tensile behaviour of the butt joints in terms of yield strength, ultimate tensile strength and ductility. In addition, microstructure

inspections and micro-hardness tests are conducted to map the location, size and the mechanical property of the soft layer in HAZ.

In numerical simulation of welding process and tensile test of S690 HSS butt joint, a new simulation method is proposed by using sequentially coupled thermal-stress analysis method which is composed of thermal analysis and stress analysis. The heat resource and welding process are defined in subroutine DFLUX under the ABAQUS modelling environment. The material deterioration in HAZ, classified by peak temperature and cooling rate, is achieved by using another two subroutines USDFLD and UEXPAN. Eight RQT S690 HSS butt joint models are built and by comparing with experimental results, including temperature history of butt joint during welding and stress-strain curves of the cut-out coupons.

In the numerical parametric study, a series of numerical models are built with same welding heat inputs of tested RQT S690 HSS butt joints based on the verified simulation method. All the models adopt the welding parameters in experiments (including welding heat input and number of welding passes), but the cooling rates $\Delta t_{8/5}$ are defined with different values of 10 s, 20 s, 30 s, 40 s, 50 s, and 60 s. After analysis, the failure mode, stress-strain curves and corresponding characteristic strength are revealed. The variation trend of characteristic strength with cooling rate are also indicated. In the end, a formulation is proposed to calculate the critical cooling rate to ensure the RQT S690 HSS butt joints satisfy the minimum mechanical requirement.

LIST OF TABLES

Table 2-1	Chemical composition of mild steel and quenched and tempered steels	11
Table 2-2	Mechanical properties at ambient temperature for quenched and tempered steel	11
Table 2-3	Stress-strain relationship expressions of RQT S690 HSS after exposure of high temperatures	21
Table 3-1	Mechanical properties of S690 HSS	47
Table 3-2	Chemical composition of S690 HSS	47
Table 3-3	Temperature difference between front surface and back surface for different target peak temperatures	51
Table 3-4	Micro-hardness at front and back surface of uniformity verification coupon	54
Table 3-5	Characteristic strength and elongation at fracture of S690 HSS after heating and cooling	70
Table 4-1	Mechanical properties of S690 HSS and weld metal	78
Table 4-2	Chemical composition of S690 HSS and weld metal	79
Table 4-3	Welding parameters of RQT S690 HSS butt joints	81
Table 4-4	Welding parameters of TMCP S690 HSS butt joints	82
Table 4-5	Four-step polishing method	92
Table 4-6	Average HAZ width of butt joints	117
Table 4-7	Mechanical property of RQT S690 HSS butt joints	122
Table 4-8	Mechanical property of TMCP S690 HSS butt joints	122
Table 4-9	Reduction factor of mechanical property of tested S690 HSS butt joints	123

Table 5-1	Welding thermal cycle information of RQT S690 HSS butt joints at 5 mm position from experiments and simplified verification models	151
Table 5-2	Characteristic strength of RQT S690 HSS butt joints from experimental and numerical results	160
Table 6-1	$\Delta t_{8/5}$ of parametric study models	165
Table 6-2	Characteristic strength of numerical models	172
Table 6-3	Calculated critical cooling time $\Delta t_{8/5,c}$ of tested S690 HSS butt joints	180

LIST OF FIGURES

Figure 2-1	Delivery condition of RQT HSS	9
Figure 2-2	Delivery condition of TMCP HSS	10
Figure 2-3	Iron-carbon equilibrium diagram	13
Figure 2-4	Microstructure of normal mild steel	14
Figure 2-5	Martensite	14
Figure 2-6	Stress-strain curves of S690 at elevated temperatures	17
Figure 2-7	Reduction factors of characteristic strength of S690 at 0.2% strain level under high temperature situation	17
Figure 2-8	Stress-strain curves of S690 after exposure to high temperatures	19
Figure 2-9	Reduction factors of characteristic strength of S690 at 0.2% strain level after exposure to high temperatures	20
Figure 2-10	SMAW	22
Figure 2-11	Coordinate system of welding heat source	23
Figure 2-12	Diagrammatic flow of heat in welding thick (a) and thin (b) plate	23
Figure 2-13	Double-ellipsoid heat source	24
Figure 2-14	Heat affected zone (Layus, Kah, Khlusova, Orlov, 2018)	26
Figure 2-15	Microstructure of coarse grained HAZ (Li, 2001) FSA-ferrite side-plate; PFG-primary ferrite on the prior austenite grain boundary; AF-acicular ferrite; P-pearlite; MA-martensite-austenite	27
Figure 2-16	Microstructure of fine-grained HAZ (Gao, Zeng, Hu, Yan, 2009)	27
Figure 2-17	Microstructure of martensite-ferrite	28

Figure 2-18	Cold crack in HAZ	29
Figure 2-19	Residual stress distribution of butt joint after welding	30
Figure 2-20	Schematic of soft zone in HAZ	32
Figure 2-21	Global buckling failure mode of slender column (Ma, Liu, Hu, Chung, Li, 2018)	34
Figure 2-22	Comparison of the FEA calculation strengths with the buckling design strength according to Eurocode 3	35
Figure 2-23	Failure mode of S690 HSS stub column (Kim, Lee, Han, Kim, Lee, Sim, 2014)	36
Figure 2-24	Diagrammatic sketches of butt joint	39
Figure 2-25	Different types of bolted T-stub connection assemblies	41
Figure 2-26	Yield lines of T-stub joint	41
Figure 3-1	Material property test device	45
Figure 3-2	Dimension of oven	46
Figure 3-3	Specimen for heating and cooling test	48
Figure 3-4	Fabrication of specimen	48
Figure 3-5	Specimen for heating and cooling test and tensile test	49
Figure 3-6	Dimension of reduced size tensile test coupon in material property study	49
Figure 3-7	Temperature history curves of heating and cooling verification test	51
Figure 3-8	Verification test setup for the specimen heated below 800 °C	52
Figure 3-9	Temperature history of specimen heated to 600 °C and 700 °C	53
Figure 3-10	Specimens for micro-hardness verification test	54
Figure 3-11	Position of Micro-hardness indentation	54

Figure 3-12	Microstructure of specimen in verification test	56
Figure 3-13	Standard coupon	57
Figure 3-14	Stress-strain curves of standard coupon and coupon in material property test	57
Figure 3-15	Stress-strain curves of coupons cooled with similar cooling rate	59
Figure 3-16	Oven with front part removed	61
Figure 3-17	Temperature history curves of specimens	64
Figure 3-18	5900R INSTRON tensile test machine	64
Figure 3-19	Typical failure mode of tensile test coupons	65
Figure 3-20	Stress-strain curves of coupons in material property test	68
Figure 3-21	Reduction factor curves of yield strength	72
Figure 3-22	Reduction factor curves of ultimate tensile strength	73
Figure 4-1	S690 HSS butt joint	80
Figure 4-2	Welding pass configuration of RQT S690 HSS butt joints	83
Figure 4-3	Welding pass configuration of TMCP S690 HSS butt joints	84
Figure 4-4	Temperature history curves of S690 HSS butt joints	89
Figure 4-5	Dimensions of butt joint and tensile test coupon	91
Figure 4-6	Specimen for microstructure and micro-hardness test	92
Figure 4-7	Light optical microscope and scanning electron microscope used in microstructure observation	93
Figure 4-8	Micro-hardness test machine	93
Figure 4-9	Locations of indentation lines for micro-hardness tests	94
Figure 4-10	Tensile test coupon	95

Figure 4-11	The 5900 series universal testing instruments	95
Figure 4-12	Microstructure of RQT S690 HSS	96
Figure 4-13	Light optical microscopy image of HAZ (RQT S690 HSS butt joint)	97
Figure 4-14	Microstructure of weld material (RQT S690 HSS butt joint)	98
Figure 4-15	Microstructure of CGHAZ (RQT S690 HSS butt joint)	99
Figure 4-16	Microstructure of FGHAZ (RQT S690 HSS butt joint)	100
Figure 4-17	Microstructures of tempering zone (RQT S690 HSS butt joint)	101
Figure 4-18	Microstructure of TMCP S690 HSS	102
Figure 4-19	Light optical microscopy image of HAZ (TMCP S690 HSS butt joint)	103
Figure 4-20	Light optical microscopy image of weld material (TMCP S690 HSS butt joint)	103
Figure 4-21	Light optical microscopy image of FGHAZ (TMCP S690 HSS butt joint)	104
Figure 4-22	Light optical microscopy image of tempering zone (TMCP S690 HSS butt joint)	104
Figure 4-23	Light optical microscopy image of CGHAZ (TMCP S690 HSS butt joint)	105
Figure 4-24	Micro-hardness test results for BJ8-3.2, BJ8-4.0 and BJ8-5.0 butt joints	108
Figure 4-25	Micro-hardness test results for BJ12-3.2 and BJ12-5.0 butt joints	110
Figure 4-26	Micro-hardness test results for BJ16-3.2, BJ16-4.0 and BJ16-5.0 butt joints	113
Figure 4-27	Micro-hardness test results for BJ22-3.2, BJ22-4.0 and BJ22-5.0 butt joints	116

Figure 4-28	Variation of average width of HAZ with welding heat input	118
Figure 4-29	Failure mode of RQT S690 HSS butt joints	119
Figure 4-30	Failure mode of TMCP S690 HSS butt joints	119
Figure 4-31	Stress-strain curves of RQT S690 HSS butt joints	121
Figure 4-32	Stress-strain curves of TMCP S690 HSS butt joints	121
Figure 5-1	Flow chart of numerical analysis	128
Figure 5-2	Double-ellipsoid heat source	128
Figure 5-3	Full plate model of butt joint	130
Figure 5-4	Engineering stress-strain curves of RQT S690 HSS at elevated temperatures	132
Figure 5-5	Ture stress-strain curves of RQT S690 HSS at elevated temperatures	133
Figure 5-6	Ture stress-strain curves of RQT S690 HSS cooling from certain peak temperatures	137
Figure 5-7	Linear interpolation method of material property definition in ABAQUS	138
Figure 5-8	Boundary condition of tensile test coupon	139
Figure 5-9	Simplified thermal analysis model	141
Figure 5-10	Temperature distribution of full joint model and coupon model during thermal analysis	142
Figure 5-11	Failure mode of coupon model	142
Figure 5-12	Temperature history curves of full joint model and coupon model for BJ8-3.2	143
Figure 5-13	Stress-strain curves of full joint model and coupon model for BJ8-3.2	144
Figure 5-14	Welding pass configuration of RQT S690 HSS butt joint verification models	146

Figure 5-15	Convection and radiation surfaces defined in simplified model	146
Figure 5-16	Comparison of temperature history curves of S690 HSS butt joints from experimental and numerical results	151
Figure 5-17	Failure mode comparison of experimental and numerical results	155
Figure 5-18	Comparison of stress-strain curves of S690 HSS butt joints from experimental and numerical results	159
Figure 6-1	Failure modes of parametric study models	167
Figure 6-2	Stress-strain curves of numerical models in parametric study	171
Figure 6-3	Relationship between R_y and $\Delta t_{8/5}$	174
Figure 6-4	Relationship between R_u and $\Delta t_{8/5}$	176
Figure 6-5	Residual stress distribution of NBJ12-5.0-10 and NBJ12-5.0-60	177
Figure 6-6	Comparison of calculated $\Delta t_{8/5}$ - R_y curves and numerical ones	180
Figure A-1	Material property definition with field values in ABAQUS	203
Figure B-1	Failure modes of parametric study models	218

LIST OF SYMBOLS

β	One parameter in Ramberg-Osgood model
ε	Strain
ε_f	Strain at fracture
$\varepsilon_{m,f}$	Strain at fracture of RQT S690 HSS in material property study
ε_T	Strain at temperature T
$\varepsilon_{p,HT}$	Proportional limit strain of S690 HSS after exposure to high temperature
ε_{Eng}	Engineering strain
ε_{Ture}	True strain
$\varepsilon_{yp,HT}$	Yield plateau strain S690 HSS after exposure to high temperature
$\varepsilon_{u,HT}$	Strain at ultimate stress of S690 HSS after exposure to high temperature
λ	Thermal conductivity of high strength steel
ρ	Density
σ_{Eng}	Engineering stress
σ_{Ture}	True stress
$\Delta t_{6/4}$	Time passing two specific temperatures 600 °C and 400 °C defined as $\Delta t_{8/5}$
$\Delta t_{8/5}$	Time passing two specific temperatures 800 °C and 500 °C defined as $\Delta t_{8/5}$
$\Delta t_{8/5,c}$	Critical cooling time with which the S690 HSS butt joint having minimum yield strength 690 MPa
A_{C1}	The temperature at which austenite begins to form during heating

Ac_3	The temperature at which transformation of ferrite to austenite is complete during heating
a_0	Coefficient in cooling time $\Delta t_{8/5}$ formula
a_{HF}	Width of molten pool
b_0	Coefficient in cooling time $\Delta t_{8/5}$ formula
b_f	Flange width of I beam
b_{HF}	Depth of molten pool
C	Specific heat capacity
CGHAZ	Coarse-grain heat affected zone
c_0	Coefficient in cooling time $\Delta t_{8/5}$ formula
c_{HF1}	Front half length of molten pool
c_{HF2}	Later half length of molten pool
d_0	Coefficient in cooling time $\Delta t_{8/5}$ formula
e_0	Coefficient in cooling time $\Delta t_{8/5}$ formula
E_T	Elastic modulus of S690 HSS at temperature T
E_n	Elastic modulus of S690 HSS at room temperature
E_{HT}	Elastic modulus of S690 HSS after exposure to high temperature
$E_{yp,HT}$	Yield plateau modulus of S690 HSS after exposure to high temperature
FGHAZ	Fine-grain heat affected zone
F_T	Tensile strength of T-stub joint
$f_{0.2,T}$	Yield strength at temperature T
f_T	Stress at temperature T
f_i	Heat distribution coefficients of front part of double-ellipsoid heat source

f_2	Heat distribution coefficients of later part of double-ellipsoid heat source
$f_{m,u}$	Ultimate tensile strength of RQT S690 HSS in material property test
$f_{m,y}$	Yield strength of RQT S690 HSS in material property test
f_u	Ultimate tensile strength
$f_{u,HT}$	Ultimate strength after exposure to high temperature
f_y	Yield strength
$f_{y,HT}$	Yield strength after exposure to high temperature
HAZ	Heat affected zone
HSS	High strength steel
I	Electric current
K_0	a Bessel function of the first kind, zero order.
L_0	Original gauge length of coupon
l_{eff}	Width of T-stub
M_S	Martensite-start temperature
M_{pl}	Moment to form plastic hinge in flange of T-stub joint
m	Distance from weld toe to center of bolt hole
n	One parameter in the Ramberg-Osgood model
n_w	Number of welding passes
p	Coefficient in stress-strain expressions of S690 HSS after exposure to high temperature
Q	Heat input power of welding
QT	Quenched and Tempered

$R_{m,f}$	Reduction factor of fracture strain of RQT S690 HSS in material property study
$R_{m,u}$	Reduction factor of ultimate tensile strength of RQT S690 HSS in material property study
$R_{m,y}$	Reduction factor of yield strength of RQT S690 HSS in material property study
R_u	Reduction factor of ultimate tensile strength of S690 HSS butt joint
R_y	Reduction factor of yield strength of S690 HSS butt joint
RQT	Reheated, quenched and tempered
q	Heat flux
q_w	Average welding heat input
r	Distance between heat source and target point
S_0	Original cross-sectional area of coupon
SEM	Scanning electron microscope
SMAW	Shield metal arc welding
T	Temperature
T_0	Initial temperature
T_p	Peak temperature
T_Q	The temperature which the sample is cooled
TMCP	Thermo-mechanically controlled processing
t	time
t_f	Flange thickness
t_p	Thickness of butt joint
U	Voltage

$V_v^{\alpha'}$	Volume fraction of martensite
V	Voltage
v	Welding speed
x	Coordinate in x direction
y	Coordinate in y direction
z	Coordinate in z direction

CHAPTER 1

INTRODUCTION

1.1 Background

Structural steel has a pivotal position in civil engineering for its light weight, high strength, prefabrication and attractive appearance. The Home Insurance Building is the first tall building using structural steel in its frame in 1885. However, the load carrying capacity of structural steel appears to be secondary to the capacity of masonry. With more than 100 years development of metallurgical technology, the mechanical performance and weldability of structural steel have been greatly improved and therefore it is widely adopted in high-rise building, bridge, stadium and offshore structure nowadays. Currently, most existed steel structures are made by mild steel, which is supported by solid research foundation and design codes, such as Eurocode 3 and AISC (BSI, 2005a; AISC, 2010). However, with higher requirement of architectural expression, living environment and economic benefits, better performance materials are necessary. High strength steel (HSS), yield stress higher than 460MPa, attracts attention of researchers for better strength to weight ratio. Higher strength to weight ratio can leads to not only smaller cross section of steel member but also less labor and transportation costs. Currently, many structures have adopted HSS as constructional material, such as Skytree tower in Tokyo, Sony Center in Berlin and Akashi Kaikyo Bridge(Miki, Homma, and Tominaga, 2002).

Generally, the mechanical performance of high strength steel (HSS) is determined by microstructures which are remarkably influenced by chemical composition and thermal history. Hence, two ways are usually adopted to enhance the strength of steel: adding alloy elements to change the chemical composition and heat treatment to

improve the microstructure. Compared with changing the chemical composition of steel, heat treatment method is preferred due to the better mechanical behaviour and weldability (Chiew, Zhao, Lee, 2014). There are two types of most favorable heat-treated high strength steel in market currently. One is Reheated, Quenched and Tempered (RQT) HSS, and the other is Thermo-Mechanically Controlled Processing (TMCP) HSS. RQT HSS is manufactured by reheated quenching and tempering process. Through the quenching process, martensite is formed under a cooling period $T_{8/5}$ of 5 to 20 seconds to provide a high strength and hardness microstructure. The tempering procedure is used to increase the toughness and ductility of steel. The whole heat treatment process can be totally independent of the mill line of steel. While, For TMCP HSS, the fabrication process consists of controlled rolling, on-line accelerated cooling and heat-treatment on-line process. Controlled rolling is to increase strength of steel by applying plastic deformation in the non-crystallization temperature range of austenite and forming transformation nucleation sites at grain's boundary and interior. The intensive and accelerated cooling procedure is aimed to gain martensite microstructure. The final heat treatment is to increase the toughness and ductility of TMCP HSS. The whole on-line system significantly increases the productivity of HSS. The detailed delivery conditions of RQT and TMCP HSS are specified in BS EN 10025-6 and -4 (BSI, 2009; BSI, 2004), respectively.

In view of the complicate heat treatment process, RQT and TMCP HSS are generally available in form of plate in order to gain uniform material properties along the plate thickness. It means that welding cannot be avoided if HSS plates are used in structural member of building, such as column, beam and joint. During welding, the weld area is generally accompanied with sever temperature changes. In fact, the heat treatment of RQT and TMCP adopted during manufacturing of HSS makes it more easily affected by high temperature (Chen, Young, Uy, 2006; Qiang, Bijlaard, Kolstein, 2012(a)) compared with normal strength steel. Experimental study shows that mechanical properties of HSS may even deteriorate significantly after welding (Zhao, Lee, Chiew, 2016; Qiang, Bijlaard, Kolstein, 2012(b)) due to the microstructure transformation of RQT and TMCP HSS, especially in heat affected zone (HAZ). Generally, a fine-grained heat affected zone (FGHAZ) will be formed (Błacha, Węglowski, Dymek and Kopuścianiński, 2016) and it is often known as a “soft layer”

owing to its inferior mechanical properties compared with original strength of base material. The strength of RQT and TMCP HSS joints is significantly affected by the mechanical property and size of the soft layer (Rodrigues, Menezes, Loureiro, Fernandes, 2004). Related research also indicates that the mechanical performance of HAZ becomes even worse with increase of welding heat input (Loureiro, 2002; Shi, Han, 2008; Kapustka, Conrardy, Babu, Albright, 2008; Akselsen, Rorvik, Onsoien, Grong, 1989; Pirinen, Martikainen, Layus, Karkhin, Ivanov, 2016).

In practice, when carrying out numerical simulation to predict the strength of HSS weld joint, the material property definition of HAZ is one of the most intricate factors since it is highly inhomogeneous caused by the involute welding thermal cycles. Many numerical investigations just simplify the inhomogeneous HAZ as a uniform area (Zhao, Lee, Fung, Chiew, 2017) and determine HAZ size by hardness test (Khurshid, Barsoum, Barsoum, 2015; Mochizuki, Shintomi, Hashimoto, Toyoda, 2004). Based on the assumption of a constant strength in the entire HAZ, the conclusion that the tensile strength of butt joint deteriorates with increase of HAZ size. The tensile strength decreases 3% to 8% in the condition of the soft layer width changing from 0.33 to 0.6 times of joint thickness (Hochhauser, Rauch, 2012). When higher welding heat input is used in simplified numerical model, width of HAZ is simply increased but without considering the corresponding material property changes. Such simplified simulation method may not be able to fully describe the HAZ behaviour, and therefore cannot show accurate evaluation of the welding impact on mechanical behaviour of HSS butt joints. In a word, although the welding influence on strength of HSS butt joints are investigated by experimental and numerical methods, there are still deficiencies in many aspects, especially in accuracy.

1.2 Objectives and Scope

As mentioned in research background, there are still many deficiencies in the investigation of welding influence on mechanical performance of HSS butt joints. Therefore, lots of work can be done in this field. This study mainly focuses on the material property of S690 HSS after cooling from different peak temperature with different rates, micro-hardness and microstructure of HAZ, the relationship between

HAZ width and welding heat input, and impact of HAZ on the mechanical performance of RQT and TMCP HSS butt joints. The main objectives of this investigation are listed as follows:

- To experimentally determine the material property of HAZ in terms of micro-hardness, microstructure, and the stress-strain curves classified by peak temperatures and cooling times $\Delta t_{8/5}$ / $\Delta t_{6/4}$,
- To experimentally explore the relationship between welding heat input and HAZ width in HSS butt joints.
- To experimentally study the influence of HAZ on the tensile behaviour of RQT and TMCP HSS butt joints.
- To numerically study the welding impact on the tensile strength of S690 HSS butt joints.

In order to achieve the mentioned objectives above, the scope of this study is summarized below:

- To experimentally achieve the temperature-dependent stress-strain curves of RQT S690 HSS. A series of coupons will be heated up from 600°C to 950°C, then cooled down to ambient temperature with different cooling rates to simulate the thermal cycles of HAZ during welding. The obtained stress-strain curves will be employed in numerical study.
- To study the microstructure of S690 HSS and the microstructure transformation of HAZ in corresponding welded butt joint. The microstructure transformation will be used to explain why the strength of S690 HSS butt joint changes after welding.
- To obtain the relationship between welding heat input and HAZ width by micro-hardness tests. The HSS butt joints will be welded by shield metal arc welding (SMAW), and different welding heat inputs are achieved by using different diameter electrodes. The HAZ width will be determined by micro-hardness tests.
- To experimentally reveal the influence of HAZ on the mechanical behaviour of RQT and TMCP HSS butt joints. Tensile test will be adopted to obtain the

stress-strain curves of HSS butt joints. Based on the stress-strain curves of butt joints, the elastic modulus, ductility and characteristic strengths (yield strength and ultimate tensile strength) will be extracted out. By comparing with the original strength of RQT and TMCP HSS, the strength deterioration of butt joints will be also indicated.

- To numerically study the welding influence on RQT S690 HSS butt joints. A new simulation method will be proposed to increase the accuracy of numerical simulation by assigning an inhomogeneous material property in HAZ according to material tests. By conducting a parametric study, a cooling time $\Delta t_{8/5}$ formula will be proposed according to the value of welding heat input q_w , number of welding passes n_w , plate thickness t_p and reduction factor of yield strength R_y . The proposed formula will also be used to obtain the critical cooling time $\Delta t_{8/5,c}$ to ensure the welded S690 HSS butt joint having the minimum yield strength 690 MPa.

1.3 Contributions and Originality

The contributions of present investigation can be summarized as an in-depth understanding of material property of S690 HSS cooling from different peak temperatures with different rates, and welding impact on the microstructure, micro-hardness and mechanical behaviour of RQT and TMCP HSS butt joints. The originality and contribution of this study include the followings:

- Explanation of material property of HAZ based on the stress-strain curves of RQT S690 HSS which are obtained by heating coupon to different peak temperatures and then cooling it down with different rates.
- Exploration of microstructure transformation and micro-hardness distribution in HAZ of S690 HSS butt joints.
- Determination of the relationship between welding heat input and HAZ width in S690 HSS butt joints by micro-hardness test and microstructure observation.

- Proposal of material changing program by using subroutines DFLUX, USDFLD and UEXPAN in ABAQUS to define the inhomogeneous property of HAZ caused by different welding heat inputs.
- Improvement of numerical modelling accuracy for investigation of welding impact on HSS butt joints by assigning inhomogeneous material property in HAZ according to peak temperature and cooling rate occurred during welding process.
- Proposal of a formula to establish the relationship between cooling time $\Delta t_{8/5}$ and reduction factor of yield strength which also can be used to determine the critical cooling time $\Delta t_{8/5,c}$ to ensure the S690 HSS butt joint with minimum yield strength 690 MPa.

1.4 Organization

The organization of this study is arranged as following:

- Chapter 2 covers literature review. Relevant research is reviewed including metallurgy of steel, the temperature impact on the material property of HSS, influence of welding on HSS members and joints, and standards for the HSS joint design.
- Chapter 3 introduces experimental investigation of material properties of S690 HSS cooled from different peak temperatures with different rates. The test specimens, method, and set-up are presented in detail. The main results are the stress-strain curves of S690 HSS which are classified by peak temperature and cooling rate, and these curves will be employed as material property of HAZ in numerical model.
- Chapter 4 reveals the influence of welding on S690 HSS butt joints by micro-hardness, microstructure observation and tensile test. The specimens, test procedure, and facilities are demonstrated. The microstructure transformation and micro-hardness distribution in HAZ are revealed to explain the existence of soft layer. The obtained stress-strain curves and

corresponding characteristic strength of butt joint are compared with original strength of HSS to reveal the welding impact on S690 HSS butt joints.

- Chapter 5 presents a new simulation method to investigate welding effect on the S690 HSS butt joints. Inhomogeneous material properties are assigned in the HAZ to increase the accuracy of numerical analysis. The numerical method is then verified by comparing with experimentally obtained temperature history curves, failure mode, stress-strain curves and characteristic strength.
- Chapter 6 demonstrates parametric study for in-depth investigation of welding impact on HSS butt joints. Cooling time $\Delta t_{8/5}$ is chosen as the investigation target. The relationship between cooling time and reduction factor of yield strength is revealed, and a corresponding formula is proposed based on the welding heating input, joint thickness and reduction factor of yield strength to describe the relationship. In addition, the formula is be used in obtain the critical cooling time $\Delta t_{8/5,c}$ to ensure the welded S690 HSS butt joint with minimum yield strength 690 MPa.
- Chapter 7 summarizes the experimental results and numerical finds, and recommendations are also given for future works based on the investigation completed in thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 High Strength Steel (HSS)

2.1.1 Overview

Currently, researchers pay much attention on High strength steel (HSS) for its higher performance in strength and corrosion resistance compared with mild steel (Qiang, Bijlaard, Kolstein, 2012a). Additionally, application of HSS also contributes to better architectural expression and economic benefits because of the high strength to weight ratio and less labor and transportation costs. Hence, HSS is increasingly being adopted in steel structure in the last few decades (Miki, Homma, Tominaga, 2002). Generally, the strength of high strength steel (HSS) is determined by microstructures which are strongly influenced by chemical composition and thermal history. Traditionally, two ways are usually adopted to enhance the strength of steel: (1) adding alloy elements to change the chemical composition and (2) employing heat treatment to improve the microstructure. Compared with changing the chemical composition of steel, the heat treatment method is preferred due to better mechanical and weldability (Chiew, Zhao, Lee, 2014).

There are two types of most favorable heat-treated high strength steel in market currently. One is Reheated, Quenched and Tempered (RQT) HSS, and the other is Thermo-Mechanically Controlled Processing (TMCP) HSS. RQT HSS is manufactured by reheated quenching and tempering steel plate. The quenching and tempering stages as described in **Figure 2-1**. In quenching stage, steel is firstly heated above critical eutectoid temperature to form austenite, then cooled down at a high rate to convert austenite into martensite rather than ferrite or pearlite in water brine, or oil (Verhoeven, 2007). Ferrite and pearlite (the typical microstructure of mild steel)

are characterized by relatively low mechanical properties and good ductility. On the contrary, as the main microstructure of HSS, martensite is quite hard but rather brittle (Rollason, 1973). Hence, tempering process is necessary to improve the ductility of HSS. The quenched steel is reheated to lower critical temperature and then cooled to ambient temperature at a low rate to transform retained austenite into bainite which is combined by ferrite and cementite. In this way, the ductility of HSS can be improved.

Figure 2-1 Delivery condition of RQT HSS

While, for TMCP HSS, the delivery condition is quite different from RQT HSS. It consists of controlled rolling, on-line accelerated cooling and heat-treatment on-line process, as presented **Figure 2-2**. The controlled rolling is the thermo-mechanically controlled processing. It is to increase strength of steel by applying plastic deformation in the non-crystallization temperature range of austenite and forming transformation nucleation sites at grain's boundary and interior. The intensive and accelerated cooling procedure is aimed to gain martensite microstructure. The final heat treatment is to increase the toughness and ductility of TMCP HSS. The whole on-line system significantly increases the productivity of HSS.

Figure 2-2 Delivery condition of TMCP HSS

The detailed delivery conditions of RQT and TMCP HSS are specified in BS EN 10025-6 and -4 (BSI, 2009; BSI, 2004), respectively. Quenching process is generally designed to cool a ferrous steel quickly, and tempering is then applied to improve the ductility and toughness of quenched steel to make sure the mechanical behaviour of steel satisfy the required level. For TMCP HSS, the on-line accelerated cooling is the quenching process, and heat-treatment on-line process is corresponding to tempering process, as shown in **Figure 2-2**.

The chemical composition of QT HSS is required to comply with specified values listed in **Table 2-1**. It can be seen that the chemical composition of QT HSS is quite similar with mild steel. Therefore, it has outstanding weldability shown out by reduced the preheating requirements and susceptibility to cold cracking (Oikawa, Murayama, Sakiyama, Takahashi, Ishikawa, 2006; Xu, Westerbaan, Nayak, Chen, Goodwin, Zhou, 2013). Compared with TMCP HSS, QT HSS generally has an increased carbon content, which leads to a decreased martensite start (M_s) and finish (M_f) temperature (Schaupp, Schroepfer, Kromm, and Kannengiesser, 2017). **Table 2-2** shows the required strength of QT HSS at room temperature. It shows that the mechanical properties of tempered and quenched steel decrease with increase of plate nominal thickness. It is similar with mild steel, since there is more metal defect with

increase of plate thickness. There is only slight difference between the stress-strain curves of RQT and TMCP and no specified selection criterion for the two kinds of HSS in practise.

Table 2-1. Chemical composition of mild steel and quenched and tempered steels

Grade	Quality	C % Max.	Si % Max.	Mn % Max.	P % Max.	S % Max.	N % Max.	B % Max.	Cr % Max.
Mild steel	JR	0.2	-	1.4	0.035	0.035	0.012	-	-
Quenched and tempered steel	L L1	0.20	0.80	1.70	0.025 0.020 0.020	0.015 0.010 0.010	0.015	0.005	1.50
Grade	Quality	Cu % Max.	Mo % Max.	Nb % Max.	Ni % Max.	Ti % Max.	V % Max.	Zr % Max.	
Mild steel	JR	0.55	-	-	-	-	-	-	
Quenched and tempered steel	L L1	0.50	0.70	0.06	2.0	0.05	0.12	0.15	

Table 2-2. Mechanical properties at ambient temperature for quenched and tempered steel

Designation	Minimum yield strength MPa Nominal thickness mm			Tensile strength MPa Nominal thickness mm			Minimum percentage elongation after fracture % $L_0 = 5.65\sqrt{S_0}$
	≥ 3 ≤ 50	> 50 ≤ 100	> 100 ≤ 150	≥ 3 ≤ 50	> 50 ≤ 100	> 100 ≤ 150	
S460Q S460QL S460QL1	460	440	400	550 to 720			17
S500Q S500QL S500QL1	500	480	440	590 to 770			17
S550Q S550QL S550QL1	550	530	490	640 to 820			16
S620Q S620QL S620QL1	620	580	560	700 to 890			15
S690Q S690QL S690QL1	690	650	630	770 to 940	760 to 930		14

S890Q S890QL S890QL1	890	830	-	940 to 1100	880 to 1000	11
S960Q S960QL	960	-	-	980 to 1150	-	10

2.1.2 Metallurgy of HSS

Steel features many microstructures and properties. It is generally formed during solid-state transformation and heat and mechanical process. In order to study steel well, it is better to start from simple composition. The behaviour of pure iron is considered firstly, and then it is the iron-carbon alloys. Finally, the steel with complex chemical compositions is investigated.

For pure iron, its ideal tensile strength of a perfect crystal is about 14200 MPa (Clatterbuck, Chrzan, Morris Jr, 2002). Nevertheless, it is not easy to gain the perfect crystal pure iron in reality, and the strength of high pure iron is also quite low due to the inevitable crystal defects in the reasonably sized samples. For example, slip occurs when the shear force as low as 10 MPa is applied on the iron in the condition of impurity content less than 60 ppm, and the yield strength of polycrystalline sample can be less than 50 MPa (Bhadeshia, Honeycombe, 2006). Generally, at least three allotropes are formed in iron, including body-centred cubic (α ferrite), face-centred cubic (γ austenite) and hexagonal closed-packed. α ferrite is stable until the temperature is heated above 910 °C (A_3 point), then transforms to γ austenite. With temperature increasing to 1390 °C (A_4 point), γ austenite reverts to ferrite which is labelled δ , although it has same crystal structure with α ferrite. The δ ferrite becomes unstable in the condition of temperature higher than 1536 °C (Hume-Rothery, 1966).

Figure 2-3 Iron-carbon equilibrium diagram

For the binary Fe-C system, there are at least three crystalline forms existing at ambient pressure, including ferrite, austenite, and cementite (Fe_3C). The equilibrium diagram of Iron-carbon in **Figure 2-3** presents the metastable equilibrium between iron and cementite. The γ -iron phase (austenite) field is much larger compared with α -iron. It means that the solubility of carbon in γ -iron is more excellent compared with α -iron. The difference existing in carbon solubility between γ -iron and α -iron makes carbon not become iron carbide as boundaries of the γ -phase field of.

Another important information revealed in this diagram is the several critical temperatures. The first one is A_{e1} (727 °C), and the eutectoid reaction occurs (P-S-K) at this temperature. The second one is A_{e3} (912 °C for pure iron). The α -iron will transform to γ -iron at this temperature. It decreases along the line GS with increase of carbon content. The third temperature is A_{e4} (1390 °C for pure iron). At this temperature, γ -iron transforms to δ -iron. When more carbon is added, the temperature is raised. In the slow cooling stage, for Fe-C alloy with 0.76 wt% carbon, the γ -iron can transform to α -iron via a eutectoid reaction at 727 °C. For the Fe-C alloy with carbon less than 0.76 wt%, austenite transforms to hypo-eutectoid ferrite when the

temperature decreases from 912 °C to 727 °C. With more austenite transforming to ferrite during slow cooling, the carbon content increases since the carbon solution of ferrite is much smaller compared with austenite. When the temperature decreases to 727 °C and the carbon increases to 0.76 wt%, the remaining austenite transforms to pearlite and cementite. In the austenite with 0.76 to 2.06 wt% carbon, if cooling rate is slow in the temperature range between 1147 °C and 727 °C, cementite firstly consumes the austenite in carbon. When the temperature reaches to 727 °C, the austenite transforms to pearlite. The three phase, ferrite, cementite and pearlite are generally the main microstructure of mild steel, as shown in **Figure 2-4**.

Figure 2-4 Microstructure of normal mild steel

Figure 2-5 Martensite

All these microstructures of mild steel generate in the condition of slow cooling, including ferrite and pearlite. If the steel with austenite is cooled rapidly to room temperature, it is generally formed martensite, which is a quite hard phase. It is the main microstructure for most HSS shown in **Figure 2-5**. The strength of steel is directly affected by the fraction of martensite. The model applied most widely to predict the fraction of martensite is the Koistinen-Marburger (K-M) equation (Koistinen, Marburger, 1959) expressed as:

$$1 - V_v^{\alpha'} = \exp\{\beta(M_s - T_Q)\} \quad \text{where } \beta \cong -0.011 \quad (2-1)$$

$V_v^{\alpha'}$ is the volume fraction of martensite. M_s is martensite-start temperature, and T_Q is the temperature which the sample is cooled. As time goes by, the K-M equation is modified by Lee and Tyne (Lee, Van Tyne, 2012) by adding an index term to $(M_s - T_Q)$, and more prediction models are proposed by many researchers. Guimaraes and Rios (Guimarães, Rios, 2013) derived a theoretical model to consider the maximum temperature of martensite embryos propagation. Lee (Lee, Lee, 2008) adopted integration of transformation rate to gain the fraction of martensite.

Although the martensite in steels can have quite high strength, its virgin condition is rather brittle. Then, it is quite necessary to conduct tempering process with the temperature changing from 150 °C to 700 °C to gain balance of strength and toughness. During tempering, the martensite precipitates and recrystallizes to an equilibrium phase. In this condition, the heat will not change the microstructure too much. At same time, the retained austenite generated during rapid cooling transforms into lower bainite (Sverdlin, and Ness Eds, 2007). As a result, the crystal defects are rearranged and eliminated, and the internal stresses are partially relieved. The ductility and toughness of steels are therefore improved finally.

Another method to improve the mechanical performance of steel is thermomechanical treatment (Barani, Li, Romano, Ponge, Raabe, 2007) which is applied by hot rolling because the process can handle vast quantities of steel and be controlled precisely and automatically. The hot rolling is designed to induces strain in steel and results in the recrystallisation of austenite to form smaller size austenite (Tamura, Sekine, Tanaka, Ouchi, 1988; Gladman, 1996). In this way, the transformed martensite from austenite during quenching process has a relatively smaller grain size

(Guo, Kim, 2001; Ohtani, Terasaki, Kunitake, 1982). Nevertheless, the high temperature has the effect of making grain size bigger. Therefore, some grain refining elements are quite necessary for the steel such as niobium, titanium and vanadium. These elements can form a strong carbide-nitrides boundary which will limit the grain size of austenite. As a result of using controlled rolling and grain refining elements, the steel with excellent mechanical property can be achieved in low alloy steels.

2.1.3 Mechanical properties of HSS at elevated temperatures

According to EN 10025-6 (BSI, 2009), S690 HSS is required to comply with yield strength 630 MPa-690 MPa and tensile strength 760 MPa-940 MPa, and the ultimate strain should be at least 14 %. While, in Eurocode 3 (EN 1993-1-12) (BSI, 2005b), the tensile strength to yield strength ratio is required to be higher than 1.05, and the ultimate strain should not be less than 10 %. Actually, the mechanical properties of S690 HSS at room temperature have been investigated experimentally in the past decade (Coelho, Bijlaard, 2007; Coelho, Bijlaard, Kolstein, 2009; Shi, Ban, Bijlaard, 2012). At room temperatures, the strength of HSS is, undoubtedly, much higher than that of mild steel. In general, the yield strength of S690 can reach above 700 MPa, and the ultimate strength is measured above 800 MPa. Nevertheless, the ductility is much lower compared with that of mild steel (Može, Beg, 2010; Može, Beg, Lopatič, 2007). For a typical S690 HSS, the ultimate strength to yield strength ratio, maximum uniform strain and fracture elongation are 1.05, 0.05 and 15 %, respectively.

Figure 2-6 Stress-strain curves of S690 at elevated temperatures

Figure 2-7 Reduction factors of characteristic strength of S690 at 0.2% strain level under high temperature situation

S690 HSS performs excellently at room temperature but is quite sensitive to high temperature which directly leads to the transformation of microstructure. Concerning the safety of S690 HSS structure under fire, its mechanical properties under high temperature are studied experimentally (Chen, Young, Uy, 2006; Chiew, Zhao, Lee, 2014; Choi, Chung, Kim, 2014; Qiang, Bijlaard, Kolstein, 2012a). **Figure 2-6** describes a group of stress-strain curves of S690 HSS at elevated temperatures (Chiew, Zhao, Lee, 2014). It shows that the strength of S690 HSS decreased with increase of temperature, but the ductility is remarkably increased at high temperatures. The deteriorated strength of S690 HSS at elevated temperatures is generally expressed by reduction factor (the ratio of strength at certain high temperature to original strength at room temperature). For example, **Figure 2-7** shows the reduction factors of characteristic strength at 0.2 % strain level at different temperatures. The characteristic strength deteriorates gently before the temperature reaches to 400 °C. In the condition of temperature ranging from 400 °C to 700 °C, the characteristic strengths decrease sharply, but become stable again when the temperature rises above 700 °C. Compared with the reduction factor of yield strength calculated based on American, Australian, British and European standards, the test values are slightly higher. Nevertheless, in the aspect of the elastic modulus, the values calculated according to design codes are generally unconservative for S690 HSS (Chen, Young, Uy, 2006).

In addition, Choi (Choi, Chung, Kim, 2014) proposed a method to predict the stress-strain curves at elevated temperatures by using the Ramberg-Osgood model (Olawale, Plank, 1988; Lee, Outinen, 1999; Mahendran, Makelainen, 2003). It is expressed as:

$$\varepsilon_T = \frac{f_T}{E_T} + \beta \left(\frac{f_{0.2,T}}{E_T} \right) \left(\frac{f_T}{f_{0.2,T}} \right)^n \quad (2-2)$$

where ε_T , f_T , $f_{0.2,T}$, E_T are strain, stress, yield strength and young's modulus at temperature T , respectively. β and n are parameters decided by the stress values and slope of the plastic region in stress-strain curve, respectively. By adjusting the parameters β and n , the proposed equation can describe the stress-strain curves of S690 HSS at elevated temperatures accurately.

2.1.4 Mechanical properties of HSS after exposure to high temperatures

As mentioned in metallurgy of HSS, after S690 HSS is heated up to certain high temperature, its main microstructure martensite will transform to austenite (γ -iron phase). During cooling, austenite can transform to low hardness microstructure such as ferrite and pearlite if the steel is cooled slowly, but also can transform to martensite or bainite under fast cooling condition which is similar to the quenching process. Considering the mechanical performance of S690 HSS could deteriorate after heating, related investigation is conducted in this field. The experiments conducted in the condition of slow cooling by Chiew (Chiew, Zhao, Lee, 2014) and Qiang (Qiang, Bijlaard, Kolstein, 2012b) revealed that the residual strength of S690 HSS after heating is related to the peak temperatures. With increase of the peak temperature, the residual strength of S690 decreases, but its ductility is remarkably improved, as presented in **Figure 2-8**. Additionally, a yield plateau normally forms in stress-strain curves of S690 HSS and the ductility also increase after exposure to elevated temperatures.

Figure 2-8 Stress-strain curves of S690 after exposure to high temperatures

Figure 2-9 Reduction factors of characteristic strength of S690 at 0.2% strain level after exposure to high temperatures

The deteriorated strength of S690 HSS after heating and cooling is also expressed by reduction factor. **Figure 2-9** illustrates the reduction factors yield strength of S690 HSS at 0.2 % strain level after cooling down from high temperatures. It can be concluded that the change of yield strength is not significant when the temperature is below 600°C, but a rapid decline can be observed between 700 °C and 900 °C. In the condition of peak temperature higher than 900 °C, only 35 % of original strength remains. Similar trend can also be observed for ultimate strength. Qiang (Qiang, Bijlaard, Kolstein, 2012b) proposed a series of expressions to predict the reduced strength of S690 HSS under post-heat condition.

The reduction factor expressions of yield strength:

$$20^{\circ}\text{C} \leq T < 650^{\circ}\text{C};$$

$$\frac{f_{y,HT}}{f_y} = 1.0 - \frac{(T-20)^{1.584}}{9957T} \quad (2-3)$$

$$650^{\circ}\text{C} \leq T \leq 1000^{\circ}\text{C};$$

$$\frac{f_{y,HT}}{f_y} = 1.80 \times 10^{-8}T^3 - 4.03 \times 10^{-5}T^2 + 2.74 \times 10^{-2}T - 4.711 \quad (2-4)$$

The reduction factor expressions of ultimate strength:

$$20^{\circ}\text{C} \leq T \leq 600^{\circ}\text{C};$$

$$\frac{f_{u,HT}}{f_u} = 1.000 \quad (2-5)$$

$$600^{\circ}\text{C} < T \leq 1000^{\circ}\text{C};$$

$$\frac{f_{u,HT}}{f_u} = -1.24 \times 10^{-10}T^4 + 4.13 \times 10^{-7}T^3 - 5.077 \times 10^{-4}T^2 + 0.27145T - 52.2 \quad (2-6)$$

Besides the strength reduction factors, the stress-strain curves of S690 HSS can also be predicted based on the expressions proposed by Tao (Tao, Wang, Uy, 2012) in **Table 2-3**. The calculated stress-strain curve describes the yield plateau of S690 HSS after heating clearly, although the accuracy is not that satisfactory.

Table 2-3 Stress-strain relationship expressions of RQT S690 HSS after exposure of high temperatures

Strain Range	Stress σ
$0 \leq \varepsilon < \varepsilon_{p,HT}$	$E_{HT} \times \varepsilon$
$\varepsilon_{p,HT} \leq \varepsilon < \varepsilon_{yp,HT}$	$f_{y,HT}$
$\varepsilon_{yp,HT} \leq \varepsilon < \varepsilon_{u,HT}$	$f_{u,HT} - (f_{u,HT} - f_{y,HT}) \times \left(\frac{\varepsilon_{u,HT} - \varepsilon}{\varepsilon_{u,HT} - \varepsilon_{yp,HT}} \right)^p$
$\varepsilon_{u,HT} \leq \varepsilon$	$f_{u,HT}$

$$p = E_n \times \left(\frac{\varepsilon_{u,HT} - \varepsilon_{yp,HT}}{f_{u,HT} - f_{y,HT}} \right)$$

$$E_{yp,HT} = 0.02E_{HT}$$

$$\varepsilon_{yp,HT} = [15 - 0.018(f_y - 300)]\varepsilon_{p,HT}$$

$$\varepsilon_{u,HT} = [100 - 0.15(f_y - 300)]\varepsilon_{p,HT}$$

Nevertheless, all these material properties are obtained in the condition of slow cooling process. Another situation involved with high temperature is welding of S690 HSS. In this condition, the steel is heated to a very high temperature and then cooled rapidly in local area (Linnert, 1967). The material properties in the heat-affected zone (HAZ) are quite different with those gained in slow cooling condition. The mechanical property of HAZ is usually indicated by hardness (Chen, Kikuta, Araki, Yoneda, Matsuda, 1984; Oikawa, Murayama, Sakiyama, Takahashi, Ishikawa, 2006;

Xu, Westerbaan, Nayak, Chen, Goodwin, Zhou, 2013; Lan, Qiu, Zhao, Gao, Du, 2011) instead of stress-strain curves due to the non-uniformity in this area. Hence, it is difficult to describe the mechanical performance of HAZ in numerical analysis because the material property of HAZ cannot be defined accurately in model only based on hardness.

2.2 Influence of Welding on High Strength Steel

2.2.1 Thermal cycle of welding

Most of S690 HSS are available in form of plate in order to gain uniform material property during quenching and tempering process. Therefore, welding is inevitable to build up structural members and joints. There are several types of welding methods in practice, such as shield metal arc welding (SMAW) shown in **Figure 2-10**, gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and submerged arc welding (SAW). The common characteristic of all the mentioned welding methods is the highly localized heat concentration around weld area.

Figure 2-10 SMAW

The heat dissipation around weld zone can be represented by the welding thermal cycle. It generally depends on the welding process and used steel, such as the heat input, thermal conductivity of steel and configuration of assembly (Kaplan D., and Murry G., 2008a). The welding process can be simplified as heat source travels with

constant speed along welding path and the thermal transferring in steel satisfies a quasi-stationary model in which the temperature redistribution near heat source uses a time-dependent stable form. The heat transfer equation is shown in equation (2-7):

$$\frac{\lambda}{\rho C} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = \frac{\partial T}{\partial t} \quad (2-7)$$

where T is temperature; t is time; λ is thermal conductivity; ρ is density and C is specific heat capacity. In stationary mode with heat source moving, the equation can be expressed as:

$$\frac{\lambda}{\rho C} \left(\frac{\partial^2 T}{\partial \xi^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) = \frac{\partial T}{\partial \xi} \quad \text{where } \frac{\partial T}{\partial t} = 0 \text{ and } \xi = x - vt \quad (2-8)$$

The coordinate system of welding heat source is demonstrated in **Figure 2-11**.

Figure 2-11 Coordinate system of welding heat source

Figure 2-12 Diagrammatic flow of heat in welding thick (a) and thin (b) plate

The resolution is firstly proposed by Rosenthal (Rosenthal D., 1946) with a series of assumptions, including steady-state heat flow, point heat source, negligible heat of fusion, constant thermal properties, no heat loss from work piece surface and no convection in the weld pool. Since the temperature transfer is different in thick plate and thin plate, the solutions are also changed. The dissipation of heat is radial for thick plate as shown in **Figure 2-12a**, while, in thin plate, the dissipation is one-dimensional presented in **Figure 2-12b**.

For thick plate welding, the temperature at any position is expressed as:

$$T = T_0 + \frac{Q}{2\pi\lambda v} e^{-\frac{v\xi\rho C}{2\lambda}} K_0 \frac{vr\rho C}{2\lambda} \quad (2.9)$$

For thin plate welding, the solution is expressed as:

$$T = T_0 + \frac{Q}{2\pi\lambda v d_w} e^{-\frac{v\xi\rho C}{2\lambda}} \frac{e^{-\frac{vr\rho C}{2\lambda}}}{r} \quad (2.10)$$

where T_0 is the initial temperature; Q is the welding energy (J); v is the welding speed; $r (\sqrt{\xi^2 + y^2 + z^2})$ is the distance between heat source and target point, and K_0 is a Bessel function of the first kind, zero order.

Figure 2-13 Double-ellipsoid heat source

All theory and equations mentioned above are based on the point heat source. As well known, there is drawback of this method. The temperature error in and around the fusion zone and HAZ is quite big (Goldak, Chakravarti, Bibby, 1984). For most of the intensive investigation on the influence of welding on HAZ, double-ellipsoid heat source model (Goldak, Chakravarti, Bibby, 1984; Bonifaz, 2000; Gery, Long, Maropoulos, 2005) is generally adopted as welding heat source shown in **Figure 2-13**. The heat flux q is calculated by the equations (2-11) and (2-12):

For the front part of heat source

$$q(x, y, z, t) = \frac{6\sqrt{3}Qf_1}{a_{HF}b_{HF}c_{HF1}\pi\sqrt{\pi}} e^{-\frac{3x^2}{a_{HF}^2} - \frac{3y^2}{b_{HF}^2} - \frac{3z^2}{c_{HF1}^2}} \quad (2-11)$$

For the rear part of heat source

$$q(x, y, z, t) = \frac{6\sqrt{3}Qf_2}{a_{HF}b_{HF}c_{HF2}\pi\sqrt{\pi}} e^{-\frac{3x^2}{a_{HF}^2} - \frac{3y^2}{b_{HF}^2} - \frac{3z^2}{c_{HF2}^2}} \quad (2-12)$$

In the Eqns. 2.11 and 2.12, f_1 and f_2 are heat distribution coefficients. a_{HF} , b_{HF} , c_{HF1} and c_{HF2} represent the shape of molten pool. x , y and z are point coordinates in heat source. Double-ellipsoid heat source model considers the non-uniformity of the energy and the geometry of molten pool, and therefore has the capability of spreading the thermal load throughout the weld pool and describe the thermal cycle of HAZ accurately. The thermal cycle of HAZ typically comprises a very fast heating and cooling phase. The intensity of cooling phase is usually characterized by cooling time $\Delta t_{8/5}$ (time used for node cooling from temperatures 800 °C and 500 °C). The reason why this parameter is important for thermal cycle of HAZ are that the final metallurgical structure in this area almost depends on the maximum temperature and $\Delta t_{8/5}$ (Kaplan, Murry, 2008b).

2.2.2 Microstructure in heat affected zone

The heat-affected zone (HAZ) generated in base material during welding process is an area where the microstructure transformation takes place as a result of welding thermal cycles (Śloderbach Z., Pająk J., 2015). The corresponding knowledge of HAZ is very important, since the microstructures in this area play an important role in the mechanical performance of joints. The HAZ could roughly divided into four parts according to the transformation of microstructure: coarse grained HAZ (CGHAZ), fine-grained HAZ (FGHAZ), intercritical HAZ, and subcritical HAZ, as shown in **Figure 2-14**.

Figure 2-14 Heat affected zone (Layus, Kah, Khlusova, Orlov, 2018)

In the procedure of welding, the peak temperatures of CGHAZ experiences is almost up to the melting point (higher than A_{c3}), which leads to the austenite grain have enough time to grow. In the consecutive fast cooling stage, the enlarged austenite is transformed to coarse martensite. (Li Y., 2001, Khan, Biro, Zhou, 2008a). That is the reason why the CGHAZ has larger grain size compared with other subzones of HAZ. The CGHAZ of HSS joint is generally accompanied with several detrimental characteristics (large prior austenite grain size, upper bainite, martensite-austenite (M-A) constituents, and microalloy precipitates) which may lead to lowest toughness in HAZ (Lee, Kim, Lee, 1989; Koo, 1987; Gibson, 2013). Among the mentioned microstructural features, the M-A constituent (crack susceptibility) plays an important role in leading to the decrease of joint toughness. The main microstructure of coarse grained HAZ is presented in **Figure 2-15**. In practice, preheating ahead of welding and post weld heat treatment are usually adopted to improve the

microstructure and reduce the adverse effect of coarse grained HAZ, (Vuherer, Maruschak, Samardzic, 2012).

Figure 2-15 Microstructure of coarse grained HAZ (Li, 2001) FSA-ferrite side-plate; PFG-primary ferrite on the prior austenite grain boundary; AF-acicular ferrite; P-pearlite; MA-martensite-austenite

Figure 2-16 Microstructure of fine-grained HAZ (Gao, Zeng, Hu, Yan, 2009)

The peak temperature of fine-grained HAZ also exceeds A_{c3} , resulting in a fully austenitized local microstructure (Khan, Biro, Zhou, 2008a). Nevertheless, the time above A_{c3} in fine-grained HAZ is short and limits the grain growth. The microstructures mainly consist of ferrite and a little of pearlite with grain size 1-3 μm , as shown in **Figure 2-16** (Gao, Zeng, Hu, Yan, 2009). Compared with martensite in coarse grain HAZ, the ferrite and pearlite in fine-grained HAZ have lower hardness, and therefore also called “soft layer” which has adverse effect on the mechanical performance of HSS welded joints.

Figure 2-17 Microstructure of martensite-ferrite

The peak temperature of intercritical HAZ is located in the range between A_{c1} and A_{c3} (Kou, 2003; Zhang, Senkara, 2011) where austenitization begins in concentration of austenite stabilizing elements (Khan M.I., Biro E., Zhou Y., 2008a). With increase of the peak temperature within this range, more and more ferrite dissolves into austenite. While, under rapid cooling after welding, the intercritical austenite can transform to a dual phase martensite-ferrite structure (shown in **Figure 2-17**) which has characteristics of high tensile strength, good hardening rate and favourable ductility (Movahed, Kolahgar, Marashi, Pournavari, Parvin, 2009; Baudin, Quesne, Jura, Penelle, 2001). While, the peak temperature of subcritical HAZ is generally below the A_{c1} . In this area, the base material of welded joint experiences a similar process of tempering. It has the least difference from base material compared with

the other three parts in the aspect of microstructure. It is well known that the final microstructures in HAZ are highly affected by welding thermal cycles and chemical composition of HSS. The microstructures in HAZ mentioned above are all formed for certain types of HSS under certain conditions. While, if the welding thermal cycles are changed or different HSS plate are used, it is hard to conclude those findings are still applicable.

2.2.3 Mechanical performance of heat affected zone

The microstructure modification in HAZ of HSS generally results in variation of mechanical property of welded joints. For example, the main microstructure of S690 HSS is tempered martensite. After welding, it may transform into bainite and martensite-austenite (M-A) constituents in CGHAZ, and ferrite and pearlite and in FGHAZ. The major modifications of mechanical performances for welded HSS joints are reflected in the aspect of toughness, fatigue, hardness and tensile strength (Kaplan, Murry, 2008b).

Figure 2-18 Cold crack in HAZ

Toughness of steel is a kind of ability to absorb energy and plastically deform without fracturing which highly depends on the microstructure of steel. In the condition of welding thermal cycles with rapid cooling, the toughness of joint could decrease drastically due to increase of the size of prior austenite grain as well as the volume fraction of bainitic ferrite and M-A constituent (Shi, Han, 2008; Khan, Kuntz, Zhou,

2008b). In this situation, cold cracking easily occurs in the local brittleness area accompanied by thermal contraction during cooling phase of welds, as shown in **Figure 2-18**. Several methods are proved useful in controlling the deterioration of toughness in HAZ. One way is to add alloy element, e.g., Bhole, et al (Bhole, Nemade, Collins, Liu, 2006), found that toughness can be improved impressively by increasing Molybdenum content to create an acicular ferrite-predominant weld metal microstructure. Controlling thermal cycle of welding is another good method. Experimental study showed if the preheat and inter-pass temperature is controlled carefully, suddenly dropping of steel toughness can be prevented (Dixon, Hakansson, 1995) and that the toughness can be enhanced by keeping the cooling time of HAZ in certain range which can be achieved by adjusting welding heat input.

(a) Longitudinal residual stress

(b) Transverse residual stress

Figure 2-19 Residual stress distribution of butt joint after welding

The fatigue performance of welded HSS joint is adversely affected by residual stress since it increases the stress level at certain area. Residual stress is normally caused by unbalanced strain which mainly comes from thermal expansion and phase transformation during welding process (Messler Jr, 2008). In the heating stage of welding, the expansion of base material near weld toe is restricted by adjacent cold parts with compressive stress forming around weld toe. In the cooling stage of welding, contract of base material near weld toe is more severe than that of adjacent area which is slightly further away from weld bead. Hence, tensile stress remains in the area around weld toe, while the adjacent areas are suffering from compression due to self-balancing of stress in plate. **Figure 2-19** describes the typical residual stress distribution of butt joint after welding.

For the investigation of residual stress caused by welding, the measurement of transient thermo-mechanical history during welding process is quite important. However, the corresponding measurement consumes lots of time and money, and cannot fully describe temperature and stress/strain distribution in specimen (Soul, Hamdy, 2012). In this situation, finite element (FE) studies are widely adopted in the studies related to welding due to the advantages of high efficiency and intuitive results. In the early years, 2-D FE models are usually employed in the investigate of residual stress due to the limitation of computer performance (Brickstad, Josefson, 1998). It cannot reflect the real situation of steel member during welding process. With the development of computing technology, 3-D models dominated the relevant research in regard to welding (Deng, Murakawa, 2006). The generation of weld is simulated by the element “birth” and “death” technique. Additionally, more factors, which affect the residual stress distribution of welded steel member, are taken into consideration in FE models to fulfil more accurate precision. For example, phase transformation effects are imported into FE models by writing program in subroutine UEXPAN in ABAQUS (Deng, 2009). Although FE analysis becomes more efficient and accurate, the simulation method still needs to be improved in many aspects. For HSS welding simulation, it does not consider the effects of material deterioration in HAZ and material properties during cooling stages on residual stress distribution. Furthermore, the finite element model needs to be adjusted and proved reliable and reasonable by comparing with experimental results as well.

Figure 2-20 Schematic of soft zone in HAZ

Hardness of steel is a compressive index which is highly dependent on ductility, elastic modulus, plasticity performance, strength, toughness, etc. Experimental study showed that the hardness of steel is directly proportional to strength which is expressed in form of empirical expressions (Cahoon, Broughton, Kutzak, 1971; Pavlina, Van Tyne, 2008). Additionally, EN ISO 18265 (BSI, 2003) also indicates the correspondence between hardness and strength. In the investigation of welding, hardness is generally employed to illustrate the mechanical property changes of HAZ. For mild steel joint, its strength is little affected by welding process, since the welding thermal cycle and very fast cooling followed result in higher strength in HAZ compared with the base material. For high strength steel, however, a soft area (with relatively lower hardness confirmed by hardness test) is generally formed in HAZ

owing to the transformation of microstructure from martensite to ferrite and pearlite (Akselsen, Rorvik, Onsoien, Grong, 1989; De Meester, 1997; Wojnowski, Oh, Indacochea, 2000). The schematic of soft zone in HAZ is illustrated in **Figure 2-20**. For certain thickness HSS plate, increase of welding heat input leads to wider soft zone and the lower mechanical properties in HAZ (Loureiro, 2002; Shi, Han, 2008; Kapustka, Conrardy, Babu, Albright, 2008; Akselsen, Rorvik, Onsoien, Grong, 1989; Pirinen, Martikainen, Layus, Karkhin, Ivanov, 2016). The existence of soft zone affects the mechanical performance of welded HSS joints (Rodrigues, Menezes, Loureiro, Fernandes, 2004; Hochhauser, Rauch, 2012).

2.3 Performance of Welded High Strength Steel Structures

The characteristics of S690 HSS, including high strength to weight ratio and good weldability (Raoul, 2005), attract researchers to use in practical engineering. The reduced weight of structures by using HSS have many favorable advantages including easy fabrication, less transportation fee and smaller foundations (Coelho, Bijlaard, 2007). Additionally, the smaller steel member sections used in construction also contributes to less consumption of steel which is an environmental benefit. Currently, the related investigation mainly focuses on column, beam, beam-column joints as well as butt joints, and the obtained results provide important data for revision and improvement of the design codes, such as American standard (AISC, 2010) and Eurocode 3 (BSI, 2005b).

2.3.1 Column

Generally, the failure mode of long column is global buckling as shown in **Figure 2-21** (Ma, Liu, Hu, Chung, Li, 2018), and the buckling performance of column is highly affected by cross section and mechanical property of structural steel. Currently, the maximum strengths of centrally loaded columns can be predicted by using the column buckling curves based on the investigation of mild steel (Ziemian, 2010; Wang, Li, Chen, Sun, 2012). For high strength steel, such as Grade S690 steel, the buckling behaviour may be different because of lower ratio of residual stress over yield strength compared with mild steel (Shi, Ban, Bijlaard, 2012). Therefore, it is not

reasonable to using such curves to predict the maximum strength of S690 HSS column. Considering this situation, tests were designed and carried out to improve the buckling curves and make design recommendations.

Figure 2-21 Global buckling failure mode of slender column (Ma, Liu, Hu, Chung, Li, 2018)

Figure 2-22 Comparison of the FEA calculation strengths with the buckling design strength according to Eurocode 3

Gang Shi, et al (Shi, Ban, Bijlaard, 2012) studied the overall buckling behaviour the high strength steel I-section columns experimentally. The tested columns were fabricated by steel grade S690 and S960. It is concluded that curve b in Eurocode 3 predicts the strength of S690 and S960 columns conservatively, and the strength calculated according to curve a is slightly higher than the column strength, as shown in **Figure 2-22**. In his later numerical investigation, new evaluation curves were proposed for strength column curves according to the Perry-Robertson formulae (Ziemian, 2010; Trahair, Bradford, Nethercot, Gardner, 2008). Modified imperfection parameters were induced in the equations (Ban H., Shi G., 2018), as listed follows:

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}}, \text{ but } \chi \leq 1.0, \text{ where } \Phi = 0.5 \left[1 + \alpha \left(\bar{\lambda} \cdot \sqrt{\frac{235}{f_y}} - 0.2 \right) + \bar{\lambda}^2 \right], \quad (2-13)$$

$$\varphi = \begin{cases} 1 - \alpha_1 \lambda_n^2, & \lambda_n \leq 0.215 \\ \frac{1}{2\lambda_n^2} \left[\left(\alpha_2 + \alpha_3 \lambda_n \cdot \sqrt{\frac{235}{f_y}} + \lambda_n^2 \right) - \sqrt{\left(\alpha_2 + \alpha_3 \lambda_n \cdot \sqrt{\frac{235}{f_y}} + \lambda_n^2 \right)^2 - 4\lambda_n^2} \right], & \lambda_n > 0.215 \end{cases}, \quad (2-14)$$

While, Li, et al (Li, Li, Chan, Wang, 2016) found the curve a was better to appraise the strength of S690 HSS columns, and same conclusion was drawn by Tianyu Ma, et al (Ma, Liu, Hu, Chung, Li, 2018) by compressing seven slender H-section columns. All the tested columns mentioned above were welded with HSS plate, and the residual stress and deformation caused by welding were considered as important

factors, although strength of high strength steel was less affected by residual stress compared with ordinary steel (Rasmussen, Hancock, 1992). For the hot-finished square and rectangular hollow section HSS columns, the residual stresses were quite low and there was no significant through-thickness bending residual stresses existed (Wang, Gardner, 2017). Therefore, the current HSS column design curves in European, North American, Chinese and Australian standards are applicable to hot finished HSS square and rectangular hollow section columns.

Figure 2-23 Failure mode of S690 HSS stub column (Gao, Sun, Jin, Fan, 2009)

For S690 HSS stub column, the failure mode is local buckling, as indicated in **Figure 2-23**, and the yield slenderness limits of ordinary steel also applied to HSS plate which is proved by test results. According to experimental results, the compressive strength of S690 stub I-section column can be determined by the strength of individual plates (Rasmussen, Hancock, 1992). Additionally, the test of box-, cruciform- and H-section S690 stub column revealed the specimens performed better when compared with the local buckling criteria in AISC (AISC, 2010) under the central and eccentric compression (Kim, Lee, Han, Kim, Lee, Sim, 2014; Gao, Sun, Jin, Fan, 2009). Same with slender column, the residual stress is also considered in those study. However, the “soft layer” in HAZ caused by welding and its impact on strength is ignored for all involved columns.

2.3.2 Beam

The main advantage of high strength steel in building construction is that cross-section of steel member is significantly reduced compared with ordinary steel, so that the problems induced by overly thick plate, such as fabrication, welding and transportation, can be avoided (Lee, Han, Uang, Kim, Park, Kim, 2012). However, the disadvantages caused by small section are the serviceability issues including excessive deflection and vibration problem. The HSS beam is also confronted with those disadvantages. James M. Ricles, et al studied the effects of local buckling on rotation capacity of HSS beam. It was revealed that the rotation capacity of flexural HSS beams was less than conventional steel ones and decreased with increase of the ratio of yield strength to tensile strength (Ricles, Sause, Green, 1998). D. Beg and L. Hladnik tried to propose a more accurate slenderness limit for welded HSS I section beams with Class 3 cross-section by experiments and numerical analysis (Beg, Hladnik, 1996). Based on investigation results, a limit slenderness of flanges, $(b_f/t_f)/(235/f_y)^{0.5} \approx 40$, was proposed. Compared with the limit for flanges $(b_f/t_f)/(235/f_y)^{0.5} \approx 30$ in accordance with Eurocode 3, the proposed equation is much more favourable. The local buckling behaviour of a hybrid beam was studied by Suzuki et al (Suzuki, Ogawa, Ikarashi, 1994). The tested beam was welded with HSS web and mild steel flange. The test results showed that the high strength steel web provided rotation restraint against local buckling for mild steel flange, and therefore degradation of strength was delayed.

Furthermore, the investigation on S690 high strength steel used in steel-concrete composite beam was also carried out by R. Shamass and K.A. Cashell (Shamass, Cashell, 2017). The composite beam consisted of HSS beam, concrete slab and stiffeners. The numerical analysis revealed that the bending strength of composite beam increased when higher strength steel was adopted. When S690 HSS was used instead of S460 HSS, the slip at the interface between the steel section and concrete slab became larger. Uy and Sloane (Uy, Sloane, 1998) also studied composite beams. However, one of conclusions was that the strength of composite HSS beams was overestimated due to absence of inherent strain hardening effects. All these

investigations expand the application of high strength steel and provide data for the design codes. However, same with the study of column, the effect of “soft layer” in HAZ on beam behaviour is still indefinite.

2.3.3 Joint

Butt joint is the most ordinary connection for steel structures and can be classified into fully penetrated joint and partially penetrated joint according to weld metal penetration levels. They also can be divided into under-matched, matched and over-matched joints according to the relative strength of the base metal and welding consumables (Khurshid, Barsoum, Barsoum, 2015). Under tension loading, the failure position of ordinary steel butt joint can be located in three sections (section A-A, section B-B, and section C-C) according to Eurcode 3, as shown in **Figure 2-24**. In the situation of fully penetrated welding, section C-C is regarded as the weak part. While, section A-A is considered as failure position for partially penetrated joints due to smaller cross section compared with base material.

(a) Fully penetrated butt joint

(b) Partially penetrated joints

Figure 2-24 Diagrammatic sketches of butt joint

For HSS butt joints, the failure modes become more complex thanks to the material deterioration in HAZ. Khurshid (Khurshid, Barsoum, Barsoum, 2015) found that fully penetrated joints with matching filler failed in the base plate. Nevertheless, Hochhauser (Hochhauser, Rauch, 2012) obtained distinct experimental results that all failure positions of penetrated joints were located in HAZ regardless the existence of weld reinforcement or not. Rodrigues (Rodrigues, Menezes, Loureiro, Fernandes, 2004) conducted numerical study on HSS butt joints without weld reinforcement. It was found that the strength of soft zone in HAZ determined the ultimate strength of joints. Generally, higher welding heat input led to larger HAZ size (Loureiro, 2002; Shi, Han, 2008; Kapustka, Conrardy, Babu, Albright, 2008; Akselsen, Rorvik, Onsoien, Grong, 1989; Pirinen, Martikainen, Layus, Karkhin, Ivanov, 2016), and HAZ width to plate thickness ratio directly affected the strength of HSS butt joints. If the ratio was less than $1/3$, the loss of strength was no more than 10% due to the constraints from adjacent area. However, when the ratio varied from $1/3$ to 1.0, significant loss of strength was observed (Rodrigues, Menezes, Loureiro, Fernandes, 2004). Nevertheless, further investigations demonstrated that the welding impact on tensile strength was limited. Tensile strength of HSS butt joint may lose 3-8%

strength when the corresponding ratio of HAZ width to plate thickness changed from 0.33 to 0.6 (Hochhauser, Rauch, 2012). The similar conclusions were also achieved by Khurshid that the soft zone in the HAZ had insignificant impact on the strength of HSS butt joint in the condition of small heat input and larger cross-section in weld (Khurshid, Barsoum, Barsoum, 2015). In numerical simulation of welding investigation, the mechanical properties of HAZ are generally simplified as mean property or defined according to micro-hardness test of HAZ. In this way, it is inconvenient to conduct parametric study, since the material properties of HAZ are highly affected by the welding thermal cycles. In order to get accurate material property, the micro-hardness test of HAZ has to be carried out for each joint.

Similar strength deterioration also occurs in welded HSS T-stub joint. T-stub joint is an important component in steel structure, as illustrated in **Figure 2-25** (Coelho, Bijlaard, Gresnigt, Da Silva, 2004). It is generally used to model the resistance of column flange in bending, end-plate in bending, flange cleat in bending and base plate in bending under tension. The failure modes and corresponding bearing capacity of T-stub joint are specified clearly in Eurocode 3: Part 1-8 (BSI, 2005c). The failure modes of T-stub joint under tension are divided into three categories according to failure positions: (1) complete yielding of flange, (2) bolt failure with yielding of flange and (3) bolt failure. Among the failure modes, complete yielding of flange is preferred in design owing to the large deform ability before failure. The corresponding bearing capacity expression is derived based on yield line theory. Four yield lines are located at both sides of welds and bolt holes in the flange of T-stub joint (Coelho, Da Silva, Bijlaard, 2004), as shown in **Figure 2-26**.

The yield lines can form plastic hinges where half of the cross-section is under tension and the other endures compression for balance. The plastic hinge can rotate freely at certain moment which balances the external force. In other words, once the plastic hinge forms, the deformation of T-stub joint keeps increasing in the condition of unchanged external force. In regard to stress concentration around the welds caused by discontinuous geometry, plastic deformation usually occurs around welds firstly as the load increases. Hence, the yield strength of flange around welds determines the calculated strength of T-stub joint in tension.

Figure 2-25 Different types of bolted T-stub connection assemblies

Figure 2-26 Yield lines of T-stub joint

The tensile behaviour of T-stub joint has been fully investigated (Coelho, Bijlaard, Gresnigt, Da Silva, 2004; Swanson, Leon, 2000; Wang, Tizani, Wang, 2010), and the tensile strength of a joint with complete flange yielding is specified in Eurocode 3: Part 1-8 as follows:

$$M_{pl} = \frac{l_{eff} t_f^2 f_y}{4} \quad (2-11)$$

$$F_T = \frac{4 \times M_{pl}}{m} \quad (2-12)$$

Where M_{pl} is the moment to form plastic hinge in flange, l_{eff} is the flange width, t_f is the thickness of flange, f_y denotes yield strength, m refers to the distance from weld toe to center of bolt hole and F_T represents the tensile strength of T-stub joint. Experimental study demonstrated that the design equations provided conservative estimates of the ultimate strength of T-stub joint with mild steel (Swanson, Leon, 2000). For HSS T-stub joints, some of the investigations showed that the tensile strength was higher compared with mild steel T-stub joints due to higher yield strength, but the plastic deformation decreased obviously (Coelho, Bijlaard, Gresnigt, Da Silva, 2004; Coelho, Bijlaard, Gresnigt, Da Silva, 2004). Further investigation showed that the ductility and maximum resistance of S690 HSS T-stub joint was improved if proper post-weld heat treatment was applied (Zhao, Chiew, Lee, 2016), and welding process could lead to deterioration of plastic resistance of T-stub joint due to the strength reduction of plastic hinges near the weld toe (Zhao, Lee, Chiew, 2016; Chen, Zhang, Zhao, Lee, Fung, Chiew, 2017). Overall, although the welding impact on tensile strength of S690 HSS butt joint is investigated recently, the influence on yield strength is still ambiguous. In the aspect of numerical analysis of welding impact, the mechanical property of HAZ could not be defined accurately, and further improvement of the simulation method is still necessary.

CHAPTER 3

MATERIAL TEST OF HSS AFTER COOLING FROM HIGH TEMPERATURES WITH DIFFERENT RATES

3.1 Introduction

Generally, the mechanical performance of high strength steel (HSS) is determined by microstructures which are heavily influenced by its chemical composition and thermal history. In general, two ways are usually adopted to enhance the strength of steel: (i) adding alloy elements to change the chemical composition and (ii) using heat treatment to improve its microstructure. Compared with changing the chemical composition of steel, heat treatment method is preferred due to better mechanical and weldability (Chiew, Zhao, Lee, 2014). The heat treatment generally consists of quenching and tempering process. In quenching stage, steel is firstly heated above critical eutectoid temperature to form austenite, then cooled down at a high rate to convert austenite into martensite rather than ferrite or pearlite in water brine, or oil (Verhoeven, 2007). Ferrite and pearlite (the typical microstructure of mild steel) are characterized by relatively low mechanical properties and good ductility. On the contrary, as the main microstructure of HSS, martensite is quite hard but rather brittle (Rollason, 1973). Hence, tempering process is necessary to improve the ductility of HSS. The quenched steel is reheated to lower critical temperature and then cooled to ambient temperature at a low rate to transform retained austenite into bainite which is combined by ferrite and cementite. In this way, the ductility of HSS can be improved.

However, the quenched and tempered HSS is susceptible to high temperature because its microstructure constitutes are not stable in this condition. During welding, it is

inevitable to go through high temperature in the HAZ, and the peak temperature of most areas is above critical eutectoid temperature. Therefore, the main microstructure of HSS, martensite, could transform to other microstructures, such as bainite, pearlite and ferrite, based on the cooling rate, or recover to martensite again if the cooling is fast enough. There is no doubt that the change of microstructure affects the mechanical performance of HAZ. Currently, the mechanical property of HAZ is reflected by hardness (Mohandas, Reddy, Kumar, 1999; Jiao, Zhao, Lau, 2015; Guo, Crowther, Francis, Thompson, Liu, Li, 2015) which is related with yield strength and tensile strength (Pavlina, Van Tyne, 2008; Cahoon, Broughton, Kutzak, 1971; Movahed, Kolahgar, Marashi, Pouranvari, Parvin, 2009). Nevertheless, this relationship does not reveal the role of welding thermal cycles, and furthermore could not describe the mechanical behaviours of HSS accurately like stress-strain curves. Some researchers tried to explain the post-heat mechanical behaviours of HSS, but the impact of cooling rate was ignored (Chiew, Zhao, Lee, 2014; Qiang, Bijlaard, Kolstein, 2012b). As a matter of fact, the cooling rate has significant effect on the micro-hardness of steels. The micro-hardness is improved under rapid cooling condition because of solid solution hardening and formation of the martensite phase (Adnan C., 2009). However, this cooling effect on mechanical behaviour of HSS is rarely shown by stress-strain curves.

In this chapter, it is mainly focused on the mechanical property of S690 HSS after it is cooled down from different peak temperatures with different cooling rates. A new tailor-made setup is designed to heat the specimen to different peak temperatures and then cool down the specimen at different cooling rates. Verification test is carried out to make sure the setup could heat and cool the coupon uniformly. The specimens are heated up to 600°C, 700°C, 800°C, 900°C and 950°C, and then cooled down with different rates by blowing air at room temperature over the specimen. The test results are demonstrated in terms of stress-strain curves obtained from different peak temperatures and cooling rates. The corresponding characteristic strengths (including yield strength and tensile strength) are also presented. The obtained material properties will be employed in numerical simulation to define the mechanical behaviour of HAZ.

3.2 Experimental Study

3.2.1 The test setup

The material property investigation is designed to measure the mechanical property of S690 HSS cooling with different rates from different peak temperatures. It is well known that the material property of HAZ is highly non-uniform since the steel within the HAZ is heated and cooled down unevenly during welding. The area close to weld, such as the CGHAZ, is generally heated up to a higher temperature compared with the FGHAZ and temper zone. The cooling rates of different positions in HAZ are different, and it is highly sensitive to the distance from weld and welding heat input. In order to reproduce the welding thermal cycle in HAZ, a special oven is designed as shown in **Figure 3-1**. The dimension of oven is 100 mm × 100 mm × 80 mm as presented in **Figure 3-2**. It is designed with two parts. The front part can be removed to facilitate cooling of the specimen after heating. The 20 mm diameter hole in front surface of oven is designed for heating. The one with 8 mm diameter located in back surface allows a thermocouple to pass through for measuring the temperature of specimen during test. There are two bars at both sides of oven used to fix the specimen.

Figure 3-1 Material property test device

Figure 3-2 Dimension of oven

External gas heater is adopted as heat source with a flame temperature of 1200 °C. It could heat the specimen in certain area up to a designated peak temperature in a reasonable short time to reproduce the heating procedure of welding. Once the

specimen is heated up to the designated peak temperature, the front part of oven and the heater will be removed immediately. Then compressed air will be blown over the specimen to increase the convection and cool down the specimen. By adjusting the pressure of compressed air to change the air flow rate, different cooling rates are then gained. In this way, the cooling stage of joint after welding can be simulated

3.2.2 Test specimen

The specimen used in test is cut out from 8 mm thickness RQT S690 HSS plate. The material property and chemical composition of used RQT S690 HSS at room temperature are listed in **Table 3-1** and **Table 3-2**, respectively. The adopted RQT S690 HSS plate satisfies the specifications in EN 10025-6 (BSI, 2009). The calculated equivalent carbon content (CE) value is 0.4 which is same with the suggested welding limit by the AWS (AWS, 2008).

Table 3-1. Mechanical properties of S690 HSS

Material	Elastic Modulus/ E (GPa)	Yield Strength/ f_y (MPa)	Ultimate Strength/ f_u (MPa)	Elongation/ ϵ_t (%)
RQT S690 HSS	208.9	745.2	837.8	14.5

Table 3-2. Chemical composition of S690 HSS

Elements	C	Si	Mn	P	S	Ni	Mo	CE
RQT S690 HSS	0.14	0.40	1.35	0.012	0.003	0.01	0.12	0.40

Figure 3-3 Specimen for heating and cooling test

The specimens used in heating and cooling tests are shown in **Figure 3-3**. All the specimens are cut out by a 2626 JetMachining Center as shown in **Figure 3-4**, and no heat is induced into specimen during cutting. Additionally, the thickness of specimen is only 3 mm. Usage of water jet could avoid machining deformation and heating the specimen. The reason why the specimen is designed with 3 mm thickness is that it could ensure the whole cross section of specimen is evenly heated. In addition, the thin plate also results in faster and more uniform cooling rate.

Figure 3-4 Fabrication of specimen

As the heating hole of the oven is 20 mm, a standard size specimen could not be heated evenly over its whole gauge length but rather only uniformly heated over at a central area with approximately in 20mm length. As a result, the standard size specimen should not be employed in direct tensile test after heating and cooling process. In order to solve this problem, a reduced size tensile test coupon is fabricated

from the specimen used in heating and cooling test, as described in **Figure 3-5** (the smaller blue central specimen), and its dimension is shown in **Figure 3-6**.

Figure 3-5 Specimen for heating and cooling test and tensile test

Figure 3-6 Dimension of reduced size tensile test coupon in material property study
The gauge length and width of tensile test coupon are 14 mm and 4 mm, respectively. This area is located in the evenly heated area (20 mm × 8 mm) of the specimen in heating and cooling test. After polishing to remove oxide layer, the coupon is ready for tensile test to obtain the corresponding stress-strain curves.

3.2.3 Reliability and consistency of the testing setup and testing procedure

The device is designed to evenly heat and cool the specimen in quite short time to simulate the condition of welding thermal cycle in HAZ. Considering the test device is a tailor-built setup built in the laboratory, it is necessary to verify its reliability and accuracy. The verification tests consist of four parts. Firstly, a check is conducted to confirm that specimen is heated and cooled uniformly. Secondly, an investigation is conducted to verify the material property of specimen is homogenous after the heating and cooling processes. Thirdly, a calibration study is carried to show that the reduced size tensile test coupon used in tests will lead to a consistent stress-strain curves which correctly describes the material property of the specimen. Finally, repeated tests are conducted to demonstrate the stability of designed device.

3.2.3.1 Heat and cooling test

During the heating and cooling processes, the specimen is heated from the front surface, and the thermocouple is placed at back surface to measure the temperature of specimen. Therefore, despite that the thickness of the specimen is thin, the temperatures at the front and back surface could be slightly different. The main aim of this verification test is to measure such slight temperature difference. In order to achieve this, two thermocouples are placed at the front and back surfaces respectively so that the temperature changes during heating and cooling stages are measured. A typical temperature history plot obtained is presented in **Figure 3-7**. The maximum temperature differences measured for the target peak temperature of 600 °C, 700 °C, 800 °C, 900 °C and 950 °C are listed in **Table 3-3**. When the target temperature of back surface is below 800 °C, the temperature difference is above 30 °C while the differences were less than 20 °C for the cases of 900 °C and 950 °C.

Figure 3-7 Temperature history curves of heating and cooling verification test

Table 3-3 Temperature difference between front surface and back surface for different target peak temperatures

Temperature difference (°C)				
600 °C	700 °C	800 °C	900°C	950°C
39.9	30.3	22.3	18.3	19.0

Figure 3-8 Verification test setup for the specimen heated below 800 °C

As it is found that the temperature differences are too large when the target temperature is below 800 °C, a small steel block (8 mm × 25 mm × 3 mm) is placed on the front surface of the specimen so that heat transfer will be mainly achieved by conduction between the small block and the specimen (**Figure 3-8**). This will be able to produce a more uniform temperature distribution and reduce the temperature differences between the front and back surface of the specimen. **Figure 3-9** shows the measured temperature history curves obtained after such adjustment of heating setup. The differences of temperatures are then reduced to 18.3 °C and 10.7 °C for 600 °C and 700 °C, respectively.

Figure 3-9 Temperature history of specimen heated to 600 °C and 700 °C

3.2.3.2 Homogeneity test

The homogeneity test is to find out whether the material property is uniform in the heated area of specimen. A specimen is first heated up to 950 °C and cooled down to room temperature with cooling time $\Delta t_{8/5}$ 60 s, and the temperature history is presented in **Figure 3-7**. After that, the heated area of specimen is cut out and divided into two parts, and then casted into cylindrical epoxy for micro-hardness test, as shown in **Figure 3-10**. The dimension of steel block is 8 mm × 8 mm (Total heated area: 20 mm × 8 mm). Micro-hardness test by Vickers (ASTM E92-17, 2017) is conducted on both front and back surface. For each surface, there are 10 points measured along both the length and the thickness directions, as described in **Figure 3-11**. The corresponding values obtained are listed in **Table 3-4**. For the front surface, the micro-hardness ranges from 371.1 Hv0.5 to 387.9 Hv0.5 with average value of 380.0 Hv0.5. For the back surface, the measured micro-hardness changes from 360.9 Hv0.5 to 383.7 Hv0.5 with average value of 374.2 Hv0.5. The micro-hardness difference is 3.5 % for the front and back surface, which is mainly caused by faster

cooling rate in the front surface which is exposed to air during cooling stage. Nevertheless, this difference is quite small.

Front surface (exposed to flame)

Back surface (contacted with thermocouple)

Figure 3-10 Specimens for micro-hardness verification test

Figure 3-11 Position of Micro-hardness indentation

Table 3-4 Micro-hardness at front and back surface of uniformity verification coupon

Surface	Hardness (Hv0.5)										Average
	1	2	3	4	5	6	7	8	9	10	
Front Surface	384.8	376.2	377.1	375.2	378.3	387.9	382.8	378.2	387.9	371.1	380.0
Back surface	378.3	383.2	375.1	377.5	366.0	360.9	369.0	367.1	383.7	381.5	374.2

Additionally, the microstructures of front and back surface are also observed under an optical microscope after the micro-hardness test. The microstructures of the two surfaces are shown in **Figure 3-12**. The microstructures of both surfaces are composed of bainitic ferrite and granular bainite, which are formed with cooling time

$\Delta t_{8/5}$ 60 s (Cui, Peng, Zhao, Peng, An and Ma, 2016). Granular bainite is composed of bainitic ferrite matrix and the martensite-austenite (M-A) phase as the second phase with typical hardness range from 287 Hv to 354 Hv (Zhang, Zhang, Li, and Liu, 2019). The hardness of bainitic ferrite can reach 650 Hv30 (Garcia-Mateo, Peet, Caballero and Bhadeshia, 2004). The microstructure composition of bainitic ferrite and granular bainite makes the micro-hardness of tested specimen in the range from 360 Hv0.5 to 390 Hv0.5. The grain size of front surface is a slightly bigger than the back surface, which is mainly caused by the slightly faster cooling rate of front surface.

(a) Microstructure of back surface

(b) Microstructure of front surface

Figure 3-12 Microstructure of specimen in verification test

Based on the micro-hardness test and microstructure observation, it can be concluded that the material property of specimen is almost uniform in the whole cross section of heated area, although the faster cooling rate in front surface leads to a little bit of higher hardness and larger grain size.

3.2.3.3 Size of the tensile test coupon

Since the tensile test coupon (presented in **Figure 3-6**) used in material property is not the standard coupon specified in EN 10002-1 (BSI, 2001), it is necessary to make sure the tested coupon can truly show the material property of S690 HSS. Therefore, a verification of tensile test coupon design is carried out. A standard full-size coupon is fabricated, and its dimension is illustrated in **Figure 3-13**. The stress-strain curve of standard coupon is compared with reduced size coupon used for direct tensile test conducted at ambient temperature as presented in **Figure 3-14**. It can be seen that the two curves are almost the same, especially in terms of yield strength and ultimate tensile strength. Therefore, conclusion can be drawn that the reduced size coupon used in direct tensile test can produce consistent stress-strain curve which describes

correctly the mechanical property of S690 HSS and no adjustment of the yield and tensile strength values is needed.

Figure 3-13 Standard coupon

Figure 3-14. Stress-strain curves of standard coupon and coupon in material property test

3.2.3.4 Reliability of the test setup

The forth verification is to check reliability and the accuracy of the test setup, test procedure and the consistency of the test results. Six specimens are heated to three different target peak temperatures of 800°C, 900°C and 950°C, and then cooled down under similar cooling rates. Tensile tests are conducted to obtain the corresponding stress-strain curves after the reduced size coupons are fabricated and polished. **Figure 3-15** illustrates the measured stress-strain curves which proves that the test device can achieve stable and consistent results. In the condition of same peak temperature and similar cooling rate, the stress-strain curves obtained are almost the same, especially in terms of elastic modulus, yield strength and ultimate tensile strength, although there is slight difference for the ductility of tested coupons.

(a) Stress-strain curves of coupons heated to 950 °C with similar cooling rate

(b) Stress-strain curves of coupons heated to 900 °C with similar cooling rate

(c) Stress-strain curves of coupons heated to 800 °C with similar cooling rate

Figure 3-15 Stress-strain curves of coupons cooled with similar cooling rate

3.2.4 Test procedure

The procedure of material property test consists of two steps. Firstly, the specimen is heated up to target temperatures (600 °C, 700 °C, 800 °C, 900 °C and 950 °C) and then cooled down to room temperature by using compressed air to achieve different cooling rates. Secondly, small tensile test coupon is fabricated out of the heated specimen. After polishing the oxide layer on coupon, tensile test is carried out to obtain the stress-strain curves.

The setup in the heating and cooling test is illustrated in **Figure 3-1**. Gas heater is employed to heat the specimen to target temperature quickly to simulate the temperature history in HAZ of joint during welding. Once the target temperature is reached, the front part of the setup is removed (**Figure 3-16**). A compressed air gun is then employed to blow air at room temperature onto the specimen to improve the convection rate. By adjusting the pressure of compressed air to change the air flow rate, different cooling rates can be obtained. For the specimens heated up to 800 °C, 900 °C and 950 °C, only the temperature of back surface is recorded as thermocouple is not attached on the front surface. However, for the specimens heated to 600 °C and 700 °C, a slightly different setup is constructed with thermocouples attached to the front and back surface. Hence, temperature history curves of both front and back surface are obtained. Additionally, the cooling time $\Delta t_{8/5}$ (time for the specimen cooling down from 800 °C to 500 °C) is measured for the specimens heated up to 800 °C, 900 °C and 950 °C, and the cooling time $\Delta t_{6/4}$ (time for the specimen cooling down from 600 °C to 400 °C) is recorded for the specimens heated to 600 °C and 700 °C. The specimen is named according to the peak temperature and the cooling time $\Delta t_{8/5}/\Delta t_{6/4}$ such that a specimen subjected to a peak temperature of 950 °C and a cooling time $\Delta t_{8/5}$ of 62.3s is labelled as 950 °C-62.3s. 17 specimens are totally tested and the obtained heating and cooling temperature history curves are presented in **Figure 3-17**. In view of the fact that the heating process is completed with the help of gas heater. There is no heating control device, and therefore the heating rate is not constant. Once the target temperature is reached, cooling process of specimen is carried out instantly without the period for maintaining the maximum temperature. The cooling time $\Delta t_{8/5}$ is controlled in the range from 10 s to 60 s.

It should be noted that according to the temperature history curves which are employed to prove the reliability of the test setup for heating and cooling test and presented in **Figure 3-7**, the temperature difference between front and back surface is about 20 °C. Based on the peak temperature of back surface, the front surface temperature can be inferred, and the difference of 20 °C is acceptable under such high temperature. Therefore, the front surface temperature is not measured during heating process, considering the difficulty and safety concern of temperature measurement of front surface. For the specimens heated up to 600 °C and 700 °C, the temperature difference between front surface and back surface should be controlled within certain range during heating, so the front surface temperature is measured to monitor the temperature difference.

Figure 3-16 Oven with front part removed

(a) Temperature history curves of specimens heated to 950 °C

(b) Temperature history curves of specimens heated to 900 °C

(c) Temperature history curves of specimens heated to 800 °C

(d) Temperature history curves of specimens heated to 700 °C

(e) Temperature history curves of specimens heated to 600 °C

Figure 3-17 Temperature history curves of specimens

Figure 3-18 5900R INSTRON tensile test machine

After the heating and cooling tests, tensile test coupons are then fabricated from the heated specimens. **Figure 3-6** shows the dimension of coupon. The gauge length of coupon is located in the uniformly heated area of heated specimen. The tensile test is conducted on a 5900R INSTRON tensile test machine according to EN 10002-1 (BSI, 2001), as presented in **Figure 3-18**. The gauge length is 14mm. In the elastic stage, the loading rate is set as 25 MP/s, and 0.001 s^{-1} is chosen as the strain rate within the plastic stage. Two strain gauges are employed to gain the strain ranging from 0 % to 1.0 %. The strain above 1.0 % is calculated based on the relative displacement of the two chucks and gauge length of coupon (relative displacement/gauge length of coupon). The tensile test is stopped until coupon fractured.

3.3 Test Results

3.3.1 Failure mode

All the tested coupons fail in gauge length which satisfies the requirement of the standard BS EN 10002-1, as shown in **Figure 3-19**. It should be noted that the gauge length area of coupon is also located in the uniformly heated area of specimen in heating and cooling test procedure.

Figure 3-19 Typical failure mode of tensile test coupons

3.3.2 Stress-strain curves

The obtained temperature- and cooling time-dependent engineering stress-strain curves are presented in **Figure 3-20**. Yield plateau is not observed in all the stress-strain curves. The elastic modulus of S690 HSS is generally not affected after the heating and cooling process, but the yield strength, ultimate tensile strength and ductility are influenced by both the peak temperature and cooling rate. The mechanical performance changes of S690 HSS are caused by the transformation of microstructure induced by heating and cooling process in test. The main microstructure of S690 HSS is tempered martensite. According to the welding

metallurgy (Koo, 1987; Kou, 2003), theoretically, if the S690 HSS is heated above A_3 (about 830 °C for steel with carbon content 0.15 %), almost all tempered martensite will be transformed to austenite. In the condition of martensite exposed to temperature between A_1 (critical temperature where the austenite begins to generate, and about 730 °C for steel with carbon content of 0.15 %) and A_3 , some martensite will be transformed to austenite. For the tempered martensite heated below A_1 , part of tempered martensite will be decomposed to ferrite, although it will not be transformed to austenite. On the other hand, the cooling rate will generally determine the final microstructure which the austenite will be transformed to after cooling. If the cooling rate is high enough, austenite will transform to martensite or bainite. In the condition of slow cooling rate, it will be transformed to ferrite, pearlite or cementite. The martensite and bainite are generally harder compared with ferrite, pearlite and cementite. Therefore, final microstructures of S690 HSS after heating and cooling determine the mechanical performance.

(a) Stress-strain curves of coupons heated up to 950 °C

(b) Stress-strain curves of coupons heated up to 900 °C

(c) Stress-strain curves of coupons heated up to 800 °C

(d) Stress-strain curves of coupons heated up to 700 °C

(e) Stress-strain curves of coupons heated up to 600 °C

Figure 3-20 Stress-strain curves of coupons in material property test

In the condition of same peak temperature, the mechanical performance of S690 HSS is improved with increase of the cooling rate (decrease of cooling time $\Delta t_{8/5}/\Delta t_{6/4}$) and this influence changes with the variation of peak temperatures. With the peak temperature ranging from 950 °C to 800 °C, the influence of cooling rate on strength of S690 HSS became stronger, and then became weaker with the continuous reduction of peak temperature from 800 °C to 600 °C. For the coupons heated to 600 °C, strength of the specimen is slightly affected by the cool time $\Delta t_{6/4}$ (36.4s and 102.7s). This could explain why there are both harder and softer zone in HAZ, as shown in **Figure 2-20**. For example, when the cooling time $\Delta t_{8/5}$ is about 20 s or 30 s, the ultimate tensile strength increases with decrease of peak temperature from 950 °C to 800 °C. As the temperature is further reduced, the ultimate tensile strength begins to decrease, and then recover to original value at 600 °C. For the specimens heated up to 700 °C, the strength is significantly deteriorated after cooling down to room temperature, since large amount of ferrite and cementite could be generated from tempered martensite under this temperature. These two kinds of microstructures have relatively lower hardness compared with tempered martensite, and therefore directly result in strength deterioration.

Additionally, the obtained stress-strain curves also show that if the cooling time $\Delta t_{8/5}$ is short enough, the mechanical property of S690 HSS can be “recovered” back to (or even be improved) the original strength after the heating and cooling process when the peak temperature is above 800 °C. It is quite important for the investigation of welded S690 HSS joint strength. When the cooling time $\Delta t_{8/5}$ is long enough, such as 60 s, the strength of HSS is generally lower compared with original one. For the coupons heated up to 700 °C, the cooling rates still affect the residual strength of post-heated S690 HSS which are all lower than the original values. In the condition of peak temperature as 600 °C, the yield strength of coupon decreases after cooling down to ambient temperature, but ultimate tensile strength of S690 HSS is almost not affected by the cooling rate.

Ductility is another important character for HSS. The stress-strain curves reveal that the ductility of S690 HSS is changed in accordance with cooling rate. In general, the ductility of post-heated S690 HSS is decreased when high cooling rate occurs in

specimen. However, for a relatively low cooling rate, the ductility is improved even compared with the original ductility. It can be explained by the fact that ferrite is generally formed due to microstructure transformation after S690 HSS is cooled from high temperature with relatively low rates. Ferrite usually has the characteristics of better ductility and toughness compared with original microstructure of HSS, such as tempered martensite. This change eventually improves the ductility of post-heat S690 HSS. The critical cooling rate, which results in same ductility with original S690 HSS, is not fixed, and it is highly depended on the peak temperature. For example, the ductility of coupon heated to 950 °C with cooling time 26.2 s is better in comparison with original material, but the ductility of coupon heated to 800 °C with cooling time 23.2 s is lower than the original one. For the coupons heated up to 600 °C and 700 °C, the ductility is improved after cooling, this also explain why such temperature range is generally employed for tempering of high strength steel to improve its toughness and ductility.

3.3.3 Characteristic strength and reduction factor

Based on the stress-strain curves, the characteristic strengths (including yield strength $f_{m,y}$ and ultimate tensile strength $f_{m,u}$) and elongation at fracture $\epsilon_{m,f}$ are listed in **Table 3-5**, as well as the corresponding reduction factors, in terms of $R_{m,y}$, $R_{m,u}$ and $R_{m,f}$. The strength at 0.2 % plastic strain is adopted as yield strength. The reduction factors are calculated as the ratio of gained characteristic strength to the original values.

Table 3-5 Characteristic strength and elongation at fracture of S690 HSS after heating and cooling

Specimen	$f_{m,y}$ (MPa)	$R_{m,y}$	$f_{m,u}$ (MPa)	$R_{m,u}$	$\epsilon_{m,f}$ (%)	$R_{m,f}$
950 °C -62.3 s	502.7	0.67	755.1	0.90	21.0	1.45
950 °C -36.4 s	589.3	0.79	821.7	0.98	16.1	1.11
950 °C -26.2 s	620.4	0.83	872.0	1.04	14.9	1.03
950 °C -11.3 s	826.4	1.11	1105.6	1.32	10.9	0.75
900 °C -60.5 s	491.9	0.66	741.4	0.88	19.0	1.31
900 °C -33.0 s	627.1	0.84	854.1	1.02	15.1	1.04
900 °C -18.0 s	662.4	0.89	932.9	1.11	13.1	0.90
900 °C -13.6 s	875.1	1.17	1132.3	1.35	10.6	0.73

800 °C -58.8 s	413.2	0.55	739.3	0.88	25.3	1.74
800 °C -30.1 s	659.9	0.89	948.7	1.13	16.1	1.11
800 °C -23.2 s	790.3	1.06	1075.5	1.28	13.6	0.94
800 °C -9.1 s	926.7	1.24	1180.3	1.41	12.4	0.86
700 °C -104.2 s	439.9	0.6	728.8	0.88	25.1	1.73
700 °C -63.1 s	486.7	0.65	741.0	0.88	21.4	1.47
700 °C -33.1 s	550.8	0.74	772.5	0.92	19.7	1.36
600 °C -102.7 s	696.2	0.93	865.7	1.03	19.0	1.31
600 °C -36.4 s	716.5	0.96	854.4	1.02	17.8	1.23

Additionally, the reduction factors of yield strength and ultimate tensile strength are plotted against the cooling time $\Delta t_{8/5}/\Delta t_{6/4}$ in **Figures 3-21** and **3-22**, respectively.

(a) Peak temperature 800 °C, 900 °C and 950 °C

(b) Peak temperature 600 °C and 700 °C

Figure 3-21 Reduction factor curves of yield strength

(a) Peak temperature 800 °C, 900 °C and 950 °C

(b) Peak temperature 600 °C and 700 °C

Figure 3-22 Reduction factor curves of ultimate tensile strength

It can be summarized based the results that both the reduction factor curves of yield and ultimate tensile strength share the same trend, although the reduction factor of yield strength is more sensitive to the cooling time compared with ultimate tensile strength. For those specimens heated up to 950 °C and 900 °C, the reduction factor of characteristic strength is gradually increased with the $\Delta t_{8/5}$ decreasing from 60 s to 20 s. When the $\Delta t_{8/5}$ is reduced from 20 s to 10 s, the increase of reduction factor becomes more intense. For the coupons heated up to 800 °C, the reduction factor almost increases linearly with the decrease of $\Delta t_{8/5}$. In the condition of cooling time less than 15 s, the reduction factors of both yield and ultimate tensile strength are higher than 1.0 for the coupons heated above 800 °C. For those specimens heated up to 600 °C and 700 °C, the characteristic strength of S690 HSS is recovered to original value with the peak temperature decreasing from 700 °C to 600 °C. Additionally, it should be noted that the influence of cooling rate on the strength of coupons heated below 700 °C became weakened compared with the ones heated above 800 °C.

3.4 Conclusions

This chapter explains experimental investigation on the material property of S690 HSS after heated to different peak temperatures and cooled with different rates. A new test device is designed and verified to be stable and accurate to conduct the heating and cooling process. A series of specimens are firstly heated to 600 °C, 700 °C, 800 °C, 900 °C and 950 °C, respectively, and then cooled down with compressed air blowing to gain different cooling rates. Following the heating and cooling test, small coupon is fabricated from the heated specimen, and tensile test is then carried out to achieve the temperature- and cooling time-dependent engineering stress-strain curves. By analyzing the obtained stress-strain curves and reduction factor of characteristic strength, conclusions can be summarized as follows:

- (1) The post-heated strength of S690 HSS is affected by both the peak temperature and cooling rate. It is mainly caused by the microstructure transformation from tempered martensite to bainite, ferrite, pearlite or cementite during heating and cooling process.
- (2) In the condition of same peak temperature, the mechanical performance of S690 HSS is improved with decrease of cooling time $\Delta t_{8/5}/\Delta t_{6/4}$, and this influence changes with variation of peak temperature. The influence of cooling rate on strength of S690 HSS becomes stronger with the peak temperature ranging from 950 °C to 800 °C, and then gets weaker with the continuous reduction of peak temperature from 800 °C to 600 °C.
- (3) The mechanical property of S690 HSS can recover to or even be higher than the original strength after heating and cooling process in the condition of peak temperature above 800 °C and short cooling time $\Delta t_{8/5}$, such as 15 s. When the cooling time $\Delta t_{8/5}$ is long enough, such as 60 s, the strength of HSS is generally lower compared with original one. For the coupons heated up to 700 °C, the cooling rates still affect the post-heated strength of S690 HSS after cooling down which are all lower than the original values. In the condition of peak temperature as 600 °C, the yield strength of coupon

decreases after cooling down to room temperature, but the cooling rate has slightly impact on the residual strength of S690 HSS.

- (4) The ductility of S690 HSS after heating changes with cooling rate. With increase of cooling rate, the ductility of post-heated S690 HSS decreases. In the condition of relatively low cooling rate, the ductility is improved compared with original material. On the other hand, once the cooling rate is high enough, the ductility becomes worse than the original one. The critical cooling rate is not fixed, and it changes with variation of peak temperature.
- (5) Both the reduction factor curves of yield and ultimate tensile strength share the same trend, although the yield strength is more sensitive to the cooling time compared with ultimate tensile strength.

CHAPTER 4

INFLUENCE OF WELDING ON TENSILE STRENGTH OF HSS BUTT JOINTS

4.1 Introduction

Among different types of HSS available in market, the reheated, quenched and tempered (RQT) and thermo-mechanical controlled process (TMCP) low alloy steel are the most commonly used S690 HSS types in structural engineering applications of HSS due to its availability and high weldability. Currently, due to limitations of the manufacturing process for achieving a highly uniform through thickness material property during the quenching and tempering process, the two kinds of low alloy high strength steels are only available in plate form. As a result, welding of HSS plates into built-up sections will be inevitable in almost all structural applications of HSS. This implies that severe temperature changes will be generated around the weld area. However, according to related investigations (Chen, Young, Uy, 2006; Qiang, Bijlaard, Kolstein, 2012a; Chiew, Zhao, Lee, 2014; Qiang, Bijlaard, Kolstein, 2012b) and the experimental study in chapter 3, it is found that the S690 HSS is generally more susceptible to the temperature changes compared with mild steel and its mechanical performance could be adversely influenced by welding.

The main reason for strength deterioration of welded S690 HSS components is the microstructure transformation in the HAZ induced by high heat input during welding. In general, depending on the microstructures, the HAZ of HSS mainly consists of three subzones, namely the coarse-grained HAZ (CGHAZ), the fine-grained HAZ (FGHAZ) and the tempering zone (Boumerzoug, Derfouf, Baudin, 2010). CGHAZ contributes the formation of the “local brittle zones” in the welded joint (Lambert-

Perlade, Gourgues, Besson, Sturel, Pineau, 2004). Within the CGHAZ, occurring of austenite grain growth often leads to the formation of bainitic microstructures after welding. The bainitic microstructures are quite vulnerable to cleavage cracking. (Lambert-Perlade, Gourgues, Pineau, 2004). In addition, the microstructure composition within the CGHAZ is seriously affected by the peak temperatures and the subsequently cooling rates. Test results show that the volume fractions of bainitic-ferrite and M-A constituent increase if the cooling time is extended, but when the cooling time is increased, the volume fraction of martensite decreases (Shi, Han, 2008). On the other hand, FGHAZ is well known as “soft layer” in the joint because its mechanical behaviour is generally lower than the base material (Wojnowski, Oh, Indacochea, 2000), especially when the joint is cooled slowly after welding. The deteriorated material property of FGHAZ is also caused by microstructure transformation. The microstructures of FGHAZ could be ferrite and pearlite which have lower hardness than tempered martensite or bainite. Previous research results show that higher welding heat input generally accompanied by a bigger FGHAZ with weaker mechanical properties (Loureiro, 2002; Shi, Han, 2008; Kapustka, Conrardy, Babu, Albright, 2008; Akselsen, Rorvik, Onsoien, Grong, 1989; Pirinen, Martikainen, Layus, Karkhin, Ivanov, 2016). Furthermore, the strength of RQT HSS joints is seriously affected by the size and mechanical properties of this soft layer (Rodrigues, Menezes, Loureiro, Fernandes, 2004; Hochhauser, Rauch, 2012; Zhao, Lee, Fung, Chiew, 2017; Chen, Zhang, Zhao, Lee, Fung, Chiew, 2017). It is also reported that the soft layer width ranging from 0.33 to 0.6 times of the plate thickness leads to the 3 % tensile strength reduction for a cooling time of 5 s and 8 % when a cooling time is reached to 18 s (Hochhauser, Rauch, 2012).

The main objective of this chapter is to conduct a series of carefully design experiments to study the welding impact on the HSS butt joints. Eleven butt joints are fabricated with 8 mm, 12 mm, 16 mm and 22 mm thickness plates by using shielded metal arc welding (SMAW). Among the plates, 8 mm, 12 mm and 16 mm plates are delivered by reheated, quenched and tempered (RQT) process, and 22 mm plate is fabricated by thermo-mechanically controlled process (TMCP). Different diameter electrodes are adopted to achieve different welding heat inputs. After the

welding procedure is complete, two coupons are directly machined out from the welded joints. Standard tensile tests are then carried out to investigate the welding impact on in terms of yield strength, ultimate tensile strength and ductility. Furthermore, the location, size and the material property of the soft layer in HAZ are investigated by microstructure inspections and micro-hardness tests are conducted.

4.2 Experimental Investigation

4.2.1 Material used

The S690 HSS employed in tests are delivered by a refined quenching and tempering (RQT) technology and thermo-mechanical control process (TMCP) for the formation of tempered martensite. The nominal yield strength of used HSS is 690 MPa and the ultimate tensile strength ranges from 790 MPa to 930 MPa. When compared with conventional QT HSS, the RQT S690 HSS plates used in this study has a higher homogeneity in the through-thickness mechanical properties. Furthermore, from the manufacturer's data, the steel plates meet with the specification of both the EN 10025-6 grade S690 (BSI, 2004) and the ASTM A514 steel (ASTM, 2009). The weld material LB-80L, which complies with the AWS A5.5 E11018-G specification (AWS, 2008), is used as filler metal for all the welding conducted in this study. **Table 4-1** lists the mechanical properties of S690 HSS and weld metal, which are obtained by standard tensile tests. **Table 4-2** shows the corresponding chemical composition (together with the carbon equivalent CE) of the used materials. The HSS plate and the filler metal used in tests have very similar yield and ultimate strength. In addition, the chemical compositions of used S690 HSS plates are quite similar with mild steel. Therefore, the HSS plates have favorable weldability, such as minimum preheating requirements during welding and low susceptibility to cold cracking (Klein, Spindler, Luger, Rauch, Stiaszny, Eigelsberger, 2005; De Meester, 1997).

Table 4-1. Mechanical properties of S690 HSS and weld metal

Material	Elastic Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
RQT S690 HSS	208.9	745.2	837.8	14.5
TMCP S690 HSS	200.1	772.6	820.8	16.3
LB-80L	210.0	767.0	848.0	22.0

Table 4-2. Chemical composition of S690 HSS and weld metal

Elements	C	Si	Mn	P	S	Ni	Mo	CE
RQT S690 HSS	0.14	0.40	1.35	0.012	0.003	0.01	0.12	0.40
TMCP S690 HSS	0.15	0.36	0.012	0.012	0.002	0.00	0.12	0.40
LB-80L	0.05	0.56	1.37	0.009	0.005	2.77	0.76	0.33

4.2.2 Joint fabrication

A total of eleven butt joints are made by welding four different thicknesses of plates including 8 mm, 12 mm, 16 mm and 22 mm. Shield metal arc welding is employed as welding method. Different welding heat inputs are obtained by using three different electrodes with diameter of 3.2 mm, 4.0 mm and 5.0 mm. During the fabrication of the joints, thermocouples are attached to the plate so that the temperature history of joint can be recorded during welding. For the two thermocouples located with 10 mm away from both ends of weld, the distance between thermocouple and bevel edge of weld is set as 10 mm. At the middle of plate, another two thermocouples are placed with the distances 5 mm and 10 mm from top edge of weld, respectively. **Figure 4-1** shows the typical configuration of welding setup.

(a) Butt joint before welding

(b) Butt joint after welding

Figure 4-1 S690 HSS butt joint

The welding parameters are enumerated in **Tables 4-3** and **4-4**, and the welding pass configurations of butt joints are shown in **Figures 4-2** and **4-3**. Note that for all joints tested in this study, the root pass is completed by using 3.2mm electrode with voltage 30 V and current 73 A, and the average heat input is 1.21 kJ/mm. additionally, it should be noted that the heat inputs per welding pass listed in **Table 4-3** and **4-4** are calculated according to EN 1011-1 (BSI, 2009). The measured temperature history curves of all joints during welding are presented in **Figure 4-4 (a)-(h)**. The RQT and TMCP S690 HSS butt joints are welded by different workers, and different welding currents are adopted for the two kinds of material considering the difference of plate thickness. For TMCP plates, larger current is employed to increase the fluidity of melted welding material. In this way, welding efficiency can be improved due to the higher deposition rate, faster welding speed and less welding passes. The measured temperature history curves of all the joints at middle of plate are described in **Figure 4-4 (i)-(k)**.

Table 4-3. Welding parameters of RQT S690 HSS butt joints

Joint	Electrode diameter (mm)	Voltage (V)	Current (A)	Pass number	Welding heat input per pass (kJ/mm)	$\Delta t_{8/5}$ (s)
BJ8-3.2	3.2	30	117	1	1.13	18.7
				2	1.33	
				3	1.17	
				4	1.36	
BJ8-4.0	4.0	30	125	1	1.37	39.2
				2	1.50	
				3	1.65	
				4	1.81	
BJ8-5.0	5.0	30	160	1	1.37	34.0
				2	1.54	
				3	1.62	
				4	1.43	
BJ12-3.2	3.2	30	117	1	1.26	-
				2	1.35	
				3	1.31	
				4	1.36	
				5	1.31	
				6	1.31	
				7	1.27	
BJ12-5.0	5.0	30	160	1	1.20	30.7
				2	1.50	
				3	2.16	
				4	1.80	
				5	1.74	
				6	1.35	
				7	1.44	
BJ16-3.2	3.2	30	117	1	1.01	12.6
				2	1.26	
				3	1.24	
				4	1.07	
				5	1.08	
				6	1.29	
				7	1.04	
				8	1.00	
				9	1.07	
				10	1.18	
				11	1.26	
				12	1.19	
				13	1.21	
				14	1.22	
				15	1.08	
				16	1.11	
BJ16-4.0	4.0	30	125	1	1.18	22.6
				2	2.04	

				3	1.78	
				4	1.82	
				5	1.53	
				6	1.41	
				7	1.43	
				8	1.44	
				9	1.93	
				10	1.60	
				11	1.41	
				1	1.12	
				2	2.00	
BJ16-5.0	5.0	30	160	3	2.54	26.0
				4	1.86	
				5	1.56	
				6	1.44	
				7	1.36	
				8	1.99	
				9	1.88	
				10	1.69	

Table 4-4. Welding parameters of TMCP S690 HSS butt joints

Specimen	Electrode diameter (mm)	Voltage (V)	Current (A)	Number of welding passes	Average heat input (kJ/mm)	$\Delta t_{8/5}$ (s)
BJ22-3.2	3.2	30.0	146	24	1.26	-
BJ22-4.0	4.0	30.0	176	18	1.69	-
BJ22-5.0	5.0	30.0	235	15	2.02	27.4

(a) BJ8-3.2, -4.0 and -5.0

(b) BJ12-3.2 and -5.0

(c) BJ16-3.2

(d) BJ16-4.0

(e) BJ16-5.0

Figure 4-2. Welding pass configuration of RQT S690 HSS butt joints

(a) BJ22-3.2

(b) BJ22-4.0

(c) BJ22-5.0

Figure 4-3. Welding pass configuration of TMCP S690 HSS butt joints

(a) BJ8-3.2

(b) BJ8-4.0

(c) BJ8-5.0

(d) BJ12-3.2

(e) BJ12-5.0

(f) BJ16-3.2

(g) BJ16-4.0

(h) BJ16-5.0

(i) BJ22-3.2

(j) BJ22-4.0

(k) BJ22-5.0

Figure 4-4 Temperature history curves of S690 HSS butt joints

From **Table 4-3**, it can be seen that the welding heat input of BJ8-5.0 is lower than that for BJ8-4.0, despite that a larger diameter electrode is employed. Such lower heat input is caused by the higher welding speed employed in the fabrication of the BJ8-5.0 joint. It is found that if the same welding speed used in the fabrication of the BJ8-4.0 joint is used, the filler material deposition rate for the BJ8-5.0 joint would be too high such that final welding quality would not be accepted. Hence, the welding speed for the BJ8-5.0 joint is increased and eventually a slightly lower than the heat input used by BJ8-4.0. The listed $\Delta t_{8/5}$ (time for the joint cooling down from 800 °C to 500 °C) is extracted from the temperature history curves recorded by thermocouples attached to the joint. For BJ12-3.2, the $\Delta t_{8/5}$ is not available since the measured peak temperature during welding is lower than 800 °C. From **Tables 4-3** and **4-4**, it is obvious that for a given plate thickness, $\Delta t_{8/5}$ is increased when higher welding heat input is used. While for the same electrode diameter (hence similar welding heat input), $\Delta t_{8/5}$ becomes shorter if the plate thickness is increased, largely due to faster heat loss due to conduction.

After the welded butt joint is cooled down, two coupons are fabricated from each joint by first machining them out from the welded plate. Then, the additional weldment covering on the joint welds is removed for a uniform cross-section. The dimensions of butt joint and the location of the tensile test coupons marked with dash lines are shown in **Figure 4-5**. Furthermore, for each joint a 50 mm × 12 mm × 8 mm rectangular block is machining out from the welding zone. This block is then divided into two halves along the center line of the weld. One half of the block is then further casted with epoxy, polished, etched with 2 % nital solution and eventually observe with both light optical microscopy and scanning electron microscope to study the detailed microstructure. The remaining one half is used for micros-hardness test to reveal the HAZ size.

micro level, and tensile test indicates the impact on joint behaviour in macro level. The specimens for microstructure observation and micro-hardness test are presented in **Figure 4-6**. The surfaces of specimens are grinded for microstructure observation and micro-hardness test. The detailed grinding process is summarized in **Table 4-5**. For the specimen used for microstructure observation, the surface is further etched with 2 % nital solution to reveal the microstructure clearly, as shown in **Figure 4-6** (a).

(a) Specimen for microstructure test

(b) Specimen for micro-hardness test

Figure 4-6 Specimen for microstructure and micro-hardness test

Table 4-5. Four-step polishing method

Step	Surface	Abrasive/size	Load (N)	Base speed (rpm)	Time (min:sec)
1	CarbiMet 2	320 grit SiC Water cooled	30	300	Until plane
2	Apex Hercules S Rigid Grinding Disc	9 μ m MetaDi Supreme Diamond	30	150	5:00
3	TriDent	3 μ m MetaDi Supreme Diamond	30	150	3:00
4	MicroCloth	0.05 μ m Master Prep Alumina	30	150	2:00

The microstructure of HAZ in RQT S690 HSS butt joints is revealed under light optical microscope and scanning electron microscope (SEM). For the TMCP S690 HSS butt joints, it is only observed under light optical microscope. The used microscopes are shown in **Figure 4-7**. Depending of the distance from the weld center, three sub-HAZs, namely CGHAZ, FGHAZ and the tempering zone, can be obtained in HAZ of HSS butt joints (Boumerzoug, Derfouf, Baudin, 2010). In microstructure

observation, all microstructure changes in the three areas and base material are observed and explained.

(a) Light optical microscope

(b) Scanning electron microscope

Figure 4-7 Light optical microscope and scanning electron microscope used in microstructure observation

Figure 4-8. Micro-hardness test machine

Figure 4-9. Locations of indentation lines for micro-hardness tests

For the micro-hardness test machine, shown in **Figure 4-8**, Vickers hardness tests using 500 g impact force are conducted to identify the boundaries between different HAZ subzones. Towards this end, a micro-hardness tester complies with the ISO 6507-1 standard (BSI, 2005d) is employed to conduct a detailed micro-hardness study. Since the butt joint is almost symmetric about the weld center line, the micro-hardness tests are only conducted on one half side of the welded joints. As shown in **Figure 4-9**, hardness tests are conducted along four indentation lines at different depths along the thickness direction of the cut-out block. The interval between any two successive indentation lines is 0.5 mm. The length of the indentation lines for the 8 mm joints are 15 mm. For the joints with thickness 12 mm and 16 mm, the length is 20 mm, while those for 22 mm joints are 25 mm. They all fully cover different parts of the cut-out block including, successively from left to right, weld material, CGHAZ, FGHAZ, tempering zone and base material.

In order to obtain the welding effects on the tensile performance of the S690 HSS butt joints, tensile tests according to EN 10002-1 (BSI, 2001) are conducted on the 22 steel coupons prepared from the 11 welded joints shown in **Figure 4-10** on universal tensile test machine shown in **Figure 4-11**. In all the direct tensile tests, the gauge length used is 50 mm, and the strain is measured by extensometer. The loading rate is set as 0.5mm/min until the fracture has taken place.

Figure 4-10 Tensile test coupon

Figure 4-11. The 5900 series universal testing instruments

4.3 Test Results

4.3.1 Microstructure of HAZ

4.3.1.1 RQT S690 HSS HAZ

As shown in the light optical microscopy and SEM images (**Figure 4-12**), the main microstructure of the RQT S690 HSS is tempered martensite. It is generated during the hardening heat and mechanical treatments and tempered at temperatures below the transformation point A_1 (approximately 730 °C for steel with CE of 0.15 %). When the S690 HSS is heated up to a temperature between the A_1 and A_3 (approximately 830 °C for steel with CE 0.15 %) and cooled down subsequently, temper martensite will transform to ferrite and austenite and eventually decomposes to ferrite, pearlite or cementite with lower hardness.

(a) Light optical microscopy image

(b) SEM image

Figure 4-12. Microstructure of RQT S690 HSS

Figure 4-13 Light optical microscopy image of HAZ (RQT S690 HSS butt joint)

(a) Light optical microscopy image of weld material

(b) SEM image of weld material

Figure 4-14 Microstructure of weld material (RQT S690 HSS butt joint)

(a) Light optical microscopy image of CGHAZ

(b) SEM image of CGHAZ

Figure 4-15 Microstructure of CGHAZ (RQT S690 HSS butt joint)

(a) Light optical microscopy image of FGHAZ

(b) SEM image of FGHAZ

Figure 4-16 Microstructure of FGHAZ (RQT S690 HSS butt joint)

(a) Light optical microscopy image of tempering zone

(b) SEM image of tempering zone

Figure 4-17 Microstructures of tempering zone (RQT S690 HSS butt joint)

Figure 4-13 shows the microstructure distributions of a typical HAZ in the RQT S690 HSS joints. It indicates that the HAZ can be subdivided CGHAZ, FGHAZ and tempering zone accordingly to their microstructures (Boumerzoug, Derfouf, Baudin, 2010; Chen, Chiew, Zhao, Lee, Fung, 2019). The CGHAZ is closest to the weld materials formed so that the highest temperature attained during welding is between A_3 and the melting point of the parent metal (about 1500 °C). It is connected to the FGHAZ within which the highest temperature attained is between the transformation temperature A_1 and the temperature A_3 . The tempering zone is a region further away from the welding material so that the maximum temperature attained is below A_1 , and relatively little phase transformation has occurred there. Typical light optical microscopy and SEM images for the weld material, the CGHAZ, the FGHAZ and the temper zone are presented in **Figures 4-14, 4-15, 4-16 and 4-17**, respectively. **Figure 4-15** illustrates the microstructure of granular bainite which consists of bainitic ferrite matrix and the martensite-austenite (M-A) phase as the second phase (Chen, Chiew, Zhao, Lee, Fung, 2019; Zhang, Zhao, Shu, He, Wang, 2017). For the FGHAZ, **Figure 4-16** shows that the tempered martensite is transformed to ferrite and cementite with

relatively low hardness after welding (Chen, Chiew, Zhao, Lee, Fung, 2019). For the temper zone, **Figure 4-17** shows the microstructure of ferrite which is formed after the decomposition of tempered martensite (Chen, Chiew, Zhao, Lee, Fung, 2019).

4.3.1.2 TMCP S690 HSS HAZ

For the TMCP S690 HSS, tempered martensite is also the main microstructure, as shown in **Figure 4-18**. **Figure 4-19** presents the joint configuration around HAZ under light optical microscopy. In the condition of 1000 $\times$ magnification, the microstructure of weld material, FGHAZ and tempering zone can be seen clearly, as shown in **Figure 4-20**, 4-21, and 4-22, respectively. Nevertheless, for TMCP joint, CGHAZ indicated in **Figure 4-23** is quite small compared with RQT one, and the narrow CGHAZ generally leads to better toughness of TMCP S690 HSS butt joint.

Figure 4-18 Microstructure of TMCP S690 HSS

Figure 4-19 Light optical microscopy image of HAZ (TMCP S690 HSS butt joint)

Figure 4-20 Light optical microscopy image of weld material (TMCP S690 HSS butt joint)

Figure 4-21 Light optical microscopy image of FGHAZ (TMCP S690 HSS butt joint)

Figure 4-22 Light optical microscopy image of tempering zone (TMCP S690 HSS butt joint)

Figure 4-23 Light optical microscopy image of CGHAZ (TMCP S690 HSS butt joint)

4.3.2 Hardness test results and size of HAZ

While the light optical microscopy and SEM images show the microstructure compositions of different subzones of the HAZ, it is not convenient to use them to determine the boundaries between different HAZ subzones in practice. Since it is well known that different microstructures associate with different hardness values, Vickers hardness tests using 500 g impact force are conducted to identify the boundaries between different HAZ subzones. The micro-hardness tests are only conducted on one half side of the welded joints since the butt joint is almost symmetric about the weld center line. The micro-hardness distributions in for the 8 mm, 12 mm and 16 mm RQT S690 HSS butt joints are shown in **Figures 4-24, 4-25, and 4-26**, respectively. For the three 22 mm TMCP S690 joints, **Figure 4-27** shows the corresponding the hardness test results.

(a) BJ8-3.2

(b) BJ8-4.0

(c) BJ8-5.0

Figure 4-24. Micro-hardness test results for BJ8-3.2, BJ8-4.0 and BJ8-5.0 butt joints

(a) BJ12-3.2

(b) BJ12-5.0

Figure 4-25 Micro-hardness test results for BJ12-3.2 and BJ12-5.0 butt joints

(a) BJ16-3.2

(b) BJ16-4.0

(d) BJ16-5.0

Figure 4-26 Micro-hardness test results for BJ16-3.2, BJ16-4.0 and BJ16-5.0 butt joints

(a) BJ22-3.2

(b) BJ22-4.0

(c) BJ22-5.0

Figure 4-27 Micro-hardness test results for BJ22-3.2, BJ22-4.0 and BJ22-5.0 butt joints

In all plots shown in **Figures 4-24 to 4-27**, the black line drawn is corresponding to the physical boundary of the plate bevel which could be confidently taken as the boundary between the weld materials and the HAZ. As the average Hv0.5 hardness value of the S690 HSS is within the range of 270 to 280, from **Figures 4-24 to 4-27**, one can easily identify the existence of a soft layer within the HAZ in which lower

hardness exists along all the indentation lines. In **Figures 4-24 to 4-27**, the two red dash lines are drawn on all plots to identify the extent of the HAZ. Therefore, by combining the results obtained from four indentation lines obtained at different through thickness locations in **Figures 4-24 to 4-27**, it is now possible to estimate the size of the HAZ produced under different plate thickness and weld heat input conditions. Additionally, it also can be seen that while for each butt welded joint the size of HAZ is roughly constant along the through-thickness direction, the HAZ width is slightly thinner at the top of the weld. This could be caused by the higher heat loss rate near the top surface (the heat transfer modes including convection, conduction and radiation) due to larger exposed area of the V-shape plate bevel configuration.

Table 4-6 Average HAZ width of butt joints

HSS	Joint name	Average HAZ width (mm)
RQT HSS	BJ8-3.2	6.84
	BJ8-4.0	8.97
	BJ8-5.0	7.59
	BJ12-3.2	6.43
	BJ12-5.0	7.19
	BJ16-3.2	5.28
	BJ16-4.0	6.03
	BJ16-5.0	7.03
TMCP HSS	BJ22-3.2	4.92
	BJ22-4.0	6.17
	BJ22-5.0	7.67

Figure 4-28 Variation of average width of HAZ with welding heat input

The average width of the HAZ is calculated by averaging the HAZ widths measured at the four different levels indentation lines. The results obtained for the eleven butt joints are listed in **Table 4-6**. The relationship between the average HAZ width and the welding heat input is presented in **Figure 4-28**. As expected, for a given plate thickness, the HAZ size is increased with welding heat input. **Figure 4-28** also shows that when similar welding heat inputs are applied to fabricate butt joint with different plate thicknesses, the average HAZ width is decreased as the plate thicknesses is increased. It can be explained by the fact that a thicker plate in general has a higher heat loss rate due to conduction, this eventually will lower the overall peak temperature profile, increase the cooling rate and then result in a narrower HAZ.

4.3.3 Tensile performance of HSS butt joint

By carefully comparing the actual failure locations of the tested RQT and TMCP S690 HSS butt joints presented in **Figures 4-29** and **4-30**, it should be noted that all butt joints coupons in tests fracture within one of the two HAZs of the coupon because

of the soft layer in HAZ. The averaged stress-strain curves obtained from the two coupon tests for each butt joint are shown in **Figures** 4-31 and 4-32. Additionally, the stress-strain curve for the original S690 HSS plate before welding is also plotted. The mechanical properties of the coupons are extracted from the stress-strain curves, such as the elastic modulus E , the yield strength f_y (taken as the 0.2 % strain offset strengths), the ultimate tensile strength f_u , ratio of tensile strength over yield strength f_u/f_y and the strain at fracture ϵ_f , and they are all summarized in **Table** 4-7 and 4-8.

Figure 4-29 Failure mode of RQT S690 HSS butt joints

Figure 4-30 Failure mode of TMCP S690 HSS butt joints

(a) Stress-strain curves of 8 mm butt joints

(b) Stress-strain curves of 12 mm butt joints

(c) Stress-strain curves of 16 mm butt joints

Figure 4-31 Stress-strain curves of RQT S690 HSS butt joints

Figure 4-32 Stress-strain curves of TMCP S690 HSS butt joints

Table 4-7 Mechanical property of RQT S690 HSS butt joints

Specimen	E (GPa)	f_y (MPa)	f_u (MPa)	f_u/f_y	ε_f (%)
RQT S690 HSS	208.9	745.2	837.8	1.12	14.5
BJ8-3.2	211.2	603.4	730.6	1.21	7.9
BJ8-4.0	209.3	542.9	686.6	1.26	9.0
BJ8-5.0	207.5	544.2	708.7	1.30	7.5
BJ12-3.2	209.9	589.8	733.0	1.24	10.6
BJ12-5.0	206.0	552.4	698.0	1.26	9.1
BJ16-3.2	215.4	641.9	772.9	1.20	10.5
BJ16-4.0	212.2	608.5	744.6	1.22	11.4
BJ16-5.0	217.1	572.5	720.5	1.26	9.7

Table 4-8 Mechanical property of TMCP S690 HSS butt joints

Specimen	E (GPa)	f_y (MPa)	f_u (MPa)	f_u/f_y	ε_f (%)
TMCP S690 HSS	200.1	772.6	820.8	1.06	16.3
BJ22-3.2	199.5	644.6	755.4	1.17	13.7
BJ22-4.0	202.7	613.5	733.3	1.20	11.1
BJ22-5.0	200.4	574.6	719.0	1.25	8.7

From the **Figures** 4-31 and 4-32 and **Tables** 4-7 and 4-8, it can be seen that when compared to the original HSS plates, both the yield strength and tensile strength of the tested RQT and TMCP S690 HSS butt joints decrease after welding and the reductions increase if higher the welding heat input is used. Such result is consistent with the hardness study results and is mainly caused by the microstructure transformations which lead to generation of a soft layer in HAZ. The deteriorated material property in soft layer eventually reduces the strength of the coupon when compared with original HSS. Additionally, when similar welding heat input is adopted to fabricate the butt joints, the strength deterioration of S690 HSS butt joint is mitigated with increase of plate thickness. That is because the thicker plate generally is accompanied with higher heat loss rate due to conduction. The high heat loss rate can lower the overall peak temperature profile and increase the cooling rate of butt joints. These two factors eventually reduce the HAZ width and mitigate the softening effect of welding on tensile behaviour of S690 HSS.

Tables 4-7 and 4-8 also indicate that the tensile strength to yield strength ratio are increased as the yield strength deteriorates more seriously than the reduction of tensile strength. Regarding the overall ductility of the coupons, it is found that

elongation at fracture of all tested butt joints are decreased after welding. As suggested in previous study (Chen, Chiew, Zhao, Lee, Fung, 2019), this could be explained by two reasons. The first reason is the high concentration of the plastic strain caused by welding (Pirinen, Martikainen, Layus, Karkhin, Ivanov, 2016). The second reason is the localized deformation within the HAZ of the butt joint coupon during the direct tensile test. During the direct tensile test of the original HSS coupon, it is found that deformation is roughly uniform distributed over the whole gauge length (50mm) before necking. However, during the direct tensile test of the butt joint coupon, it is found that localized deformation at the HAZ is much larger than the remaining part of the coupon. As the size of the HAZ is smaller than the gauge length (e.g. for the BJ8-3.2 joint, the size of the HAZ is only 6.84 mm), when the HAZ reached the fracture limit and caused the coupon to fail, the overall elongation over the whole gauge length is still smaller than the corresponding origin HSS coupon.

Additionally, according to the material property study presented in Chapter 3, the post-heat ductility of S690 HSS can be improved with decrease of cooling rate, which is mainly caused by the formation of ferrite. In the FGHAZ, there is ferrite formed after welding, and it means the ductility of the HAZ is better compared with base material. Nevertheless, the deformation of welded butt joints is mainly limited within the HAZ during tensile test. Compared with uniform deformation in whole gauge length of original flat plate coupon before necking, the deformation of HAZ is too small which eventually leads to the serious deterioration of ductility.

Table 4-9 Reduction factor of mechanical property of tested S690 HSS butt joints

HSS	Specimen	Average welding heat input (kJ/mm)	R_y	R_u
RQT HSS	BJ8-3.2	1.25	0.81	0.87
	BJ8-4.0	1.58	0.73	0.82
	BJ8-5.0	1.49	0.73	0.85
	BJ12-3.2	1.31	0.79	0.87
	BJ12-5.0	1.60	0.74	0.83
	BJ16-3.2	1.14	0.86	0.92
	BJ16-4.0	1.60	0.82	0.89
	BJ16-5.0	1.74	0.77	0.86
TMCP HSS	BJ22-3.2	1.26	0.83	0.92
	BJ22-4.0	1.69	0.79	0.89
	BJ22-5.0	2.02	0.74	0.87

Note:

R_y =yield strength of butt joint / yield strength of S690 HSS

R_u =tensile strength of butt joint / tensile strength of S690 HSS

The deteriorated mechanical property of S690 HSS butt joint can also be expressed as the reduction factor for the yield strength R_y and the reduction factor for the ultimate strength R_u . **Table 4-9** shows the values of R_y and R_u for the joints tested in this study. It can be seen that the reduction factor of yield strength R_y ranges from 0.73 to 0.86 while the reduction factor of tensile strength varying from 0.82 to 0.92 for tested RQT S690 HSS butt joints. On the other hand, for TMCP S690 HSS butt joints, the reduction factor of yield strength R_y ranges from 0.74 to 0.83 while the reduction factor of tensile strength R_u varying from 0.87 to 0.92.

4.4 CONCLUSIONS

This chapter reports the results obtained from an experimental study on the welding influence on HSS butt joints. Eight joints are fabricated by welding RQT S690 HSS plates with thickness 8 mm, 12 mm and 16 mm, and another three joints are welded with 22 mm thickness TMCP S690 HSS by using shielded metal arc welding (SMAW). After welding, microstructure investigation and micro-hardness test are employed to inspect the microstructure transformations detailly within the heat affect zone (HAZ). In addition, tensile test coupons are carefully fabricated from the joints and standard direct tensile tests are conducted to reveal the welding effects on the welded joints. According to the experimental results, the following conclusions are obtained.

- (1) The light optical microscopy and SEM images reveal that, after welding of RQT S690 HSS, the tempered martensite of base material is transformed to granular bainite in the CGHAZ and to ferrite and cementite in the FGHAZ. For the tempering zone further away from the weld, some of the tempered martensite decomposed to ferrite. For TMCP S690 HSS, the main difference from RQT HSS is that the area of CGHAZ is quite small, and its microstructure is not the granular bainite. This variation in CGHAZ of TMCP

S690 HSS butt joint is generally good for the toughness and ductility of welded HSS joints.

- (2) By conducting a detailed micro-hardness tests at four different levels along the thickness direction of the butt joint, the extent of the soft layer in FGHAZ due to the microstructure transformation is determined. The micro-hardness tests confirm that the HAZ width increases as welding heat input is increased. While, in the condition of similar welding heating input, the HAZ size is decreased with increase of plate thickness.
- (3) Tensile tests show that all the RQT and TMCP S690 HSS butt joints tested have lower strength compared with the original HSS. In addition, RQT and TMCP HSS butt joints have same failure mode, and they all fractured within the HAZ with lower ultimate tensile strength and worse ductility. Detailed analysis of the tensile test results shows that for a given plate thickness, both the yield strength and the ultimate tensile strength reduction factors decrease as the welding heat input increases. However, for a similar level of welding heat input, the both reduction factors increase as the plate thickness increases. Furthermore, the welding influence on strength reduction is quite similar for both RQT and TMCP S690 HSS butt joints. The reduction factor of yield strength R_y ranges from 0.73 to 0.86 while the reduction factor of tensile strength varying from 0.82 to 0.92 for tested RQT S690 HSS butt joints. On the other hand, for TMCP S690 HSS butt joints, the reduction factor of yield strength R_y ranges from 0.74 to 0.83 while the reduction factor of tensile strength R_u varying from 0.87 to 0.92.

The test results reveal that the mechanical performance of S690 HSS butt joint deteriorates after welding when compared with original material. Nevertheless, it is also indicated a fast cooling rate (caused by lower heat input and thicker plates) could improve the tensile behaviour of welded HSS joints. Therefore, it is worthwhile and important to conduct further investigations to find out the critical cooling rate which could make the S690 HSS butt joint to retrain the same tensile strength as the S690 HSS plates.

CHAPTER 5

NUMERICAL INVESTIGATION OF WELDING IMPACT ON HSS BUTT JOINTS

5.1 Introduction

Based on the material property study and investigation of welding impact on S690 HSS butt joint, it can be summarized that the S690 HSS is sensitive to high temperature and welding process. The microstructure transformation in HAZ caused by welding thermal cycles directly affects the tensile strength of welded butt joints. The experimental investigation can reveal the welding influence on the microstructure, micro-hardness in HAZ and mechanical behaviour of S690 HSS butt joint, but more time and resource are necessary to achieve the goal. Thus, it is impractical to only rely on experimental study to fully understand the impacts of welding for different welding configuration applied in constructions. Among the available analyzing methods, finite element simulation has been widely employed in the study of residual strength distribution and deteriorated static strength of HSS joint caused by welding process as result of negligible cost, high efficiency and the ability of describing a complete picture of temperature and stress/strain distribution. In the early stage, 2-D finite element model is adopted thanks to the limitation of computer performance. However, 2-D model cannot show the whole picture of joint during welding because many factors are ignored, such as generation of weld and phase transformation. With the development of computer technology, 3-D models are developed, and more and more factors are taken into consideration. For example, the “birth” and “death” of element technique is adopted to simulate the generation of weld, and phase transformation effect is imported into finite element model by writing program in form of a user-defined subroutine UEXPAN as well. In addition,

the deterioration of material property is also considered in FE models. In most existing numerical analysis, the mechanical properties of steel deteriorate during heating, and then recover after cooling down to room temperature. This assumption is reasonable for mild steel, because the welded normal steel butt joint generally fractures at base material. However, for high strength steel after exposure to high temperature, the deterioration of material cannot be ignored. Recently, a simplified modelling method was proposed and takes material deterioration in HAZ into consideration for high strength steel (Khurshid, Barsoum, Barsoum, 2015). Nevertheless, this method needs the area of HAZ and corresponding homogenized material properties which can only be obtained by hardness test. The test processes significantly limit the efficiency of numerical study.

In this chapter, another simulation method is proposed to study the impact of welding process on static strength of S690 HSS butt joints by using ABAQUS. The numerical models are built with sequentially coupled thermal-stress analysis method which is composed of thermal analysis and stress analysis. The heat resource and welding process are defined in a user-defined subroutine DFLUX (inside the ABAQUS finite element analysis package). The material deterioration in HAZ, classified by peak temperature and cooling rate, is achieved by using the subroutines USDFLD and UEXPAN. Eight RQT S690 HSS butt joint models are built and analyzed, and verification is conducted by comparing with the experimental results in terms of temperature history and stress-strain curves of the cut-out coupons.

5.2 Thermal Analysis Model

5.2.1 Double ellipsoid heat source

In ABAQUS, sequentially coupled thermal-stress analysis method is composed of two separate analyses, including thermal analysis and stress analysis. The thermal analysis model is established to obtain the temperature history of each node. Then, the temperature history is input into stress analysis as field variable. In stress analysis model, the mechanical property of steel changes according to the temperature history. Therefore, the mesh of thermal analysis model should be exactly same as stress analysis model. The flow chart of whole analysis is described in **Figure 5-1**.

Figure 5-1 Flow chart of numerical analysis

Figure 5-2 Double-ellipsoid heat source

In thermal analysis model, double ellipsoid heat source is determined by the user-defined subroutine DFLUX to simulate the welding heat source of SMAW, as shown in **Figure 5-2**. The corresponding program is shown in APPENDIX A. The heat flux q can be obtained by the following equations:

For the front part of heat source

$$q(x, y, z, t) = \frac{6\sqrt{3}Qf_1}{a_{HF}b_{HF}c_{HF1}\pi\sqrt{\pi}} e^{-\frac{3x^2}{a_{HF}^2} - \frac{3y^2}{b_{HF}^2} - \frac{3z^2}{c_{HF1}^2}} \quad (5-1)$$

For the rear part of heat source

$$q(x, y, z, t) = \frac{6\sqrt{3}Qf_1}{a_{HF}b_{HF}c_{HF2}\pi\sqrt{\pi}} e^{-\frac{3x^2}{a_{HF}^2} - \frac{3y^2}{b_{HF}^2} - \frac{3z^2}{c_{HF2}^2}} \quad (5-2)$$

$$Q = \eta UI \quad (5-3)$$

In equations (5-1) and (5-2), f_1 and f_2 are fractions of deposited heat. The sum of f_1 and f_2 should be 2. Considering there is more energy distributed in the front part of heat source, 1.33 and 0.67 are assigned to f_1 and f_2 , respectively. a_{HF} , b_{HF} , c_{HF1} and c_{HF2} describes the shape of heat source. The welding heat input Q is calculated by multiplying thermal efficient factor η , voltage U and current I . In EN BS. 1011-1 (BSI, 2009), η is 0.8 for SMAW. The values of U and I are same with the ones used in tests as listed in **Table 4-3**.

5.2.2 Thermal property definition

In thermal analysis model, the thermal properties of S690 HSS are defined as temperature-dependent ones. The density of steel is 7850 kg/m³, and the latent heat is 300 kJ/kg with liquidus temperature 1480 °C and solidus temperature 1430 °C. According to the specification in EC3: part 1-2 (BSI, 2005a), the specific heat c_a (J/(kg°C)) can be calculated by the equations (5-4), (5-5), (5-6) and (5-7), and conductivity λ_a (W/(m°C)) is determined based on the equations (5-8) and (5-9).

For 20 °C ≤ T < 600 °C;

$$c_a = 425 + 7.73 \times 10^{-1}T - 1.69 \times 10^{-3}T^2 + 2.22 \times 10^{-6}T^3 \quad (5-4)$$

For 600 °C ≤ T < 735 °C;

$$c_a = 666 + \frac{13002}{738-T} \quad (5-5)$$

For 735 °C ≤ T < 900 °C;

$$c_a = 545 + \frac{17820}{T-731} \quad (5-6)$$

For 900 °C ≤ T ≤ 1200 °C;

$$c_a = 650 \quad (5-7)$$

For 20 °C ≤ T < 800 °C;

$$\lambda_a = 54 - 3.33 \cdot 10^{-2}T \quad (5-8)$$

For 800 °C ≤ T ≤ 1200 °C;

$$\lambda_a = 27.3 \quad (5-9)$$

5.2.3 Mesh and boundary condition

A full butt joint model with plate thickness 8 mm is established according to the dimension of BJ8-3.2 in **Figure 4-5**. In order to realistically reproduce the experimental process, two tensile test coupon models are also built in the full plate model, and “birth” and “death” of element technique is adopted to achieve the generation of weld and the cutting out procedure of tensile test coupons. The full joint model is shown in **Figure 5-3**.

Figure 5-3 Full plate model of butt joint

The mesh is refined in weld and HAZ due to dramatic temperature change in this area with element size 1.0 mm, and transitional elements are used to connect coarse and meticulous mesh. The whole model of HSS butt joint consists of 25482 solid elements. DC3D8 (an 8-node linear heat transfer brick) is adopted as element type in thermal analysis model. In the aspect of thermal boundary condition, convection and radiation are considered in model. The ambient temperature is assigned with 31 °C for thermal analysis model according to the temperature of HSS plate before welding. The convection coefficient is 25 W/(m²·°C), and the radiation coefficient is 0.5

5.3 Stress Analysis Model

5.3.1 Mechanical property definition

In stress analysis model, the mechanical property definitions of S690 HSS at elevated temperatures and after cooling down to room temperature are quite complex for welding influence analysis. On one hand, the characteristic strength, such as yield strength and ultimate tensile strength, is affected not only by the peak temperature but also by the cooling rate. On the other hand, the material property is highly inhomogeneous in HAZ of welded butt joint.

Previous FE simulation method generally simplified the HAZ as a homogeneous material with deteriorated material property or divided the HAZ into several homogenous parts and each of them is then assigned with different but uniform mechanical property to reflect the non-uniformity of the HAZ. Nevertheless, those methods significantly limit the accuracy and efficiency of numerical study. In order to improve the modelling accuracy, the user-defined subroutines USDFLD and UEXPAN are adopted to assign the material property in node level according to the peak temperature and cooling rate.

The expansion coefficient ε_T is defined in UEXPAN according to the equations in EC3: part 1-2 (BSI, 2005a) as follows:

For $20^\circ\text{C} \leq T < 750^\circ\text{C}$;

$$\varepsilon_T = 1.2 \times 10^{-5}T + 0.4 \times 10^{-8}T^2 - 2.416 \times 10^{-4} \quad (5-10)$$

For $750^\circ\text{C} \leq T \leq 860^\circ\text{C}$;

$$\varepsilon_T = 1.2 \times 10^{-2} \quad (5-11)$$

For $750^\circ\text{C} < T \leq 1200^\circ\text{C}$;

$$\varepsilon_T = 2 \times 10^{-5}T - 6.2 \times 10^{-3} \quad (5-12)$$

The material property of S690 HSS at elevated temperature is defined according to the experimental results from Chiew, S.P. (Chiew, Zhao, Lee, 2014) **Figure 5-4** shows the corresponding engineering stress-strain curves. However, these engineering curves cannot be used directly in ABAQUS due to high nonlinear behaviour of material and geometry. Hence, true stress-strain curves should be calculated according the equations (5-13) and (5-14):

$$\varepsilon_{\text{True}} = \ln(1 + \varepsilon_{\text{Eng}}) \quad (5-13)$$

$$\sigma_{\text{True}} = \sigma_{\text{Eng}}(1 + \varepsilon_{\text{Eng}}) \quad (5-14)$$

where σ_{True} and $\varepsilon_{\text{True}}$ are the true stress and strain, respectively; σ_{Eng} and ε_{Eng} is the engineering stress and strain, respectively. **Figure 5-5** shows the calculated true stress-strain curves which are input in ABAQUS by two parts. One is elastic part where the strength increases linearly with strain. The other part is the non-linear part which starts from yield strength, and it is defined with plastic strain in ABAQUS. The group of temperature-dependent stress-strain curves of S690 HSS under heating process is defined with field values in ABAQUS. The example of material property definition is demonstrated in APPENDX A.

Figure 5-4 Engineering stress-strain curves of RQT S690 HSS at elevated temperatures

Figure 5-5 True stress-strain curves of RQT S690 HSS at elevated temperatures

The mechanical property of RQT S690 HSS cooling from certain peak temperatures are also defined in ABAQUS according to the test results in Chapter 3. The engineering stress-strain curves are shown in **Figure 3-20**. The equations (5-13) and (5-14) are only used to calculate the true stress-strain curves of post-heat S690 HSS with strain up to the ultimate tensile strength. Beyond the ultimate tensile strength, the stress is kept unchanged with increase of strain. This definition of material property may result in less accuracy of predicated strength when the deformation of butt joint extends beyond necking but has negligible effect on the predicted characteristic strength, such as yield strength and ultimate strength of welded S690 HSS butt joints. The corresponding true stress-strain curves grouped by peak temperature and cooling rate are presented in **Figure 5-6**. When the peak temperature is below 600 °C, the strength of RQT S690 HSS recovers to original value, and cooling rate has slightly impact on the mechanical property. Same with the stress-strain curves at elevated temperatures, the post-heating ones are also divided into elastic and yield parts and defined with field values in ABAQUS. The peak

temperature is defined in field 1. The cooling time $\Delta t_{6/4}$ and $\Delta t_{8/5}$ are defined in field 2 and field 3, respectively.

In ABAQUS, there is a function to linearly interpolate the input stress-strain curves automatically, so that the stress-strain curves at any peak temperature with any cooling time can be obtained by linearly interpolation and assigned to node according to the temperature history curves (ABAQUS, 2012). It can be divided into several situations. Firstly, it is the peak temperature and cooling rate which the node goes through during analysis are out of the defined ranges for the stress-strain curves. In this situation, the stress-strain curves with highest temperature and longest/shortest cooling time will be defined to those nodes. For example, if the peak temperature and cooling time $\Delta t_{8/5}$ the node going through are 1000 °C and 70 s, respectively, the stress-strain curves defined with 950 °C-62.3 s (shown in **Figure 5-6(a)**) will be assigned to node. Secondly, it is the peak temperature which the node goes through during analysis in the defined range, but the cooling time is out of the defined range. In this condition, the stress-strain curve will be calculated by linear interpolation based on the defined peak temperatures and longest/shortest cooling times. For example, the node in HAZ is heated up to 930 °C and then cooled down with cooling time $\Delta t_{8/5}$ 10 s. The stress-strain curves named 950 °C-11.3 s and 900 °C-13.6 s will be used to gain corresponding material property by linear interpolation based on peak temperatures. Thirdly, it is the peak temperature which the node goes through during analysis out of the defined range, but the cooling time is in the defined range. Similar with the second situation, the stress-strain curve will be calculated by linear interpolation based on the defined highest peak temperatures and cooling times. For example, the node in HAZ is heated up to 1000 °C and then cooled down with cooling time $\Delta t_{8/5}$ 20 s. The stress-strain curves named 950 °C-11.3 s and 950 °C- 26.2 s will be used to gain corresponding material property by linear interpolation based on the two cooling times. Finally, it is both the peak temperature and cooling time in the range of defined material property. In this condition, the linear interpolation will be used three times to gain the corresponding stress-strain curve. For example, the node in HAZ is heated up to 930 °C and then cooled down with cooling time $\Delta t_{8/5}$ 20 s. In the first step, the stress-strain curves 950 °C-11.3 s and 950 °C- 26.2 s will be

interpolated linearly to gain the curve with peak temperature 950 °C and cooling time $\Delta t_{8/5}$ 20 s. In the second step, the stress-strain curves 900 °C-18.0 s and 900 °C- 33.0 s will be interpolated linearly to gain the curve with peak temperature 900 °C and cooling time $\Delta t_{8/5}$ 20 s. In the third step, the obtained two curves are interpolated linearly again by using the peak temperature 950 °C and 900 °C to achieve the stress-strain curves with peak temperature 930 °C and cooling time $\Delta t_{8/5}$ 20 s. The example of forth situation is described in a flow chart, as shown in **Figure 5-7**.

For the material property of weld, it is assumed to have same mechanical property with original RQT S690 HSS at room temperature according to micro-hardness test results of weld. During heating process, the material property changes with increase of temperature, and the corresponding stress-strain curves are shown in **Figure 5-5**. After the temperature decreases to room temperature, the strength recovers to original values which is not affected by the cooling rate.

(a) Stress-strain curves with peak temperature 950 °C

(b) Stress-strain curves with peak temperature 900 °C

(c) Stress-strain curves with peak temperature 800 °C

(d) Stress-strain curves with peak temperature 700 °C

(e) Stress-strain curves with peak temperature 600 °C

Figure 5-6 True stress-strain curves of RQT S690 HSS cooling from certain peak temperatures

Figure 5-7 Linear interpolation method of material property definition in ABAQUS

By using the user-defined subroutines USDFLD and UEXPAN, the material property changes induced by the welding thermal cycle will be defined in HAZ (at nodal level in the FE model) based on the temperature history obtained from thermal analysis. In the subroutine UEXPAN, the peak temperature of every node is recorded for each welding pass. If the peak temperature is lower than 800 °C, the cooling time $\Delta t_{6/4}$ (time for node to cool down from 600 °C to 400 °C) will be recorded. For the node with peak temperature higher than 800 °C, the cooling time $\Delta t_{8/5}$ (time for node to cool down from 800 °C to 500 °C) is measured. The recorded peak temperature and corresponding cooling time $\Delta t_{6/4}$ / $\Delta t_{8/5}$ will be replaced by new ones if the following welding pass leads to higher peak temperature for the node. After the welding process is completed and butt joint is cooled down to ambient temperature, the field values are finally determined based on the peak temperature and the cooling time. In USDFLD, the peak temperature is then assigned to field 1. The cooling time $\Delta t_{6/4}$ is defined to field 2 in the condition of peak temperature lower than 800 °C, and the cooling time $\Delta t_{8/5}$ is assigned to field 3 when the peak temperature is higher than 800

°C. Based on these values, the corresponding stress-strain curve will be calculated by linear interpolation, chosen from the data base (stress-strain curves shown in **Figure 5-8**) and then assigned to node. The programs of subroutines DFLUX, USDFLD and UEXPAN are shown in APPENDIX A.

5.3.2 Mesh and boundary condition

The mesh of stress model is completely the same with the thermal analysis model shown in **Figure 5-3**, so that the temperature history curve of each node can be directly transferred between the two models. During welding, physical boundary is applied on the plate joint to ensure that the joint position is fixed, and expansion caused by high temperature is not restricted. When the welding process is completed, “birth” and “death” of element technique is adopted to cut out the tensile test coupon for the following tensile test analysis.

Figure 5-8 Boundary condition of tensile test coupon

Additionally, it is well known that the residual stress has some impact on the stiffness and stability of welded HSS members (Sun, Liang, and Zhao, 2019). In the stress analysis model, the residual stress was actually considered. The residual stress is formed in stress analysis model due to the thermal expansion and contraction of butt

joint after the temperature history of welded joint is imported from thermal analysis model to stress analysis model. After this, the direct tensile test of butt joint is simulated on the coupon model with residual stress. In this way, the effect of residual strength on the direct tensile test performance of S690 HSS butt joints is considered in the proposed simulation method.

An 8-node linear brick element (C3D8) is chosen as element type, and the boundary condition of coupon is presented in **Figure 5-8**. Both ends of coupon are fixed before tension. While, in tensile procedure, displacement load is exerted on coupon. After the analysis is completed, the stress-strain curves of S690 HSS butt joints can be obtained to compare with test results for verification of numerical model.

5.4 Simplified Model

The proposed modelling method truly reproduces the experimental process of welding influence on S690 HSS butt joints. Nevertheless, the full butt joint model consumes large amount of time for analyzing due to a large number of elements used (25482 elements), especially during thermal analysis. The computer with 40 cores (Intel (R) Xeon (R) CPU E5-2630 v3 @ 2.40 GHz 2.40 GHz) and 128G RAM takes about 4 days to complete the four-pass welding process with more than 12000 increments for each welding pass, and this significantly limits the analyzing efficiency and practicality, especially in parametric study. Therefore, it is necessary to simplify the model to save analyzing time but to maintain the reliability and accuracy the analysis results.

Since welding heat input is constant for each pass, it is assumed the width of butt joint (150 mm, shown in **Figure 4-5**) has limited effect on the experimental results. The full butt joint model of BJ8-3.2 in thermal analysis is then simplified to a coupon model which is same with the one for stress analysis except for the weld reinforcement, as shown in **Figure 5-9**. During stress analysis, the weld reinforcement is deactivated in the first step by death of element to achieve the uniform cross-section of tensile test coupon. The temperature distribution of full joint model and coupon model is presented in **Figure 5-10**. The failure mode and position

of the two models are same that the fracture is occurred within the HAZ. The failure mode of coupon model is shown in **Figure 5-11**. Additionally, comparison between full model and coupon model is also carried out in terms of temperature history curves and stress-strain curves. **Figure 5-12** indicates the temperature history curves of two points at middle of full model and coupon model during welding. The distance 5 mm and 10 mm mean the distance between the measured points to the bevel edge of the weld at top surface. It can be observed that the temperature in full model is slightly lower compared with the coupon model since the larger volume of full model increases the heat conduction within joint. In addition, compared with coupon the model, the larger surface area of full model also accelerates heat loss by convection and radiation.

Figure 5-9 Simplified thermal analysis model

(a) Temperature distribution of full joint model

(b) Temperature distribution of coupon model

Figure 5-10 Temperature distribution of full joint model and coupon model during thermal analysis

Figure 5-11 Failure mode of coupon model

Figure 5-13 presents the stress-strain curves of full joint model and coupon model. The stress-strain curve of coupon model is almost same with the one of full joint model, although the ultimate strength of full model is a little higher than the coupon model. That is mainly caused by the relatively lower peak temperature and faster cooling rate in full model, as shown in **Figure 5-12**. Nevertheless, this slight difference between full model and coupon results is totally acceptable especially under the premise of drastically reduced analysis time.

Figure 5-12 Temperature history curves of full joint model and coupon model for BJ8-3.2

Figure 5-13 Stress-strain curves of full joint model and coupon model for BJ8-3.2

Based on the simplified modelling method, eight verification models are built for the RQT S690 HSS butt joints, since only the material property of RQT S690 HSS are tested in Chapter 3. Additionally, according to microstructure and micro-hardness test in HAZ of RQT and TMCP S690 HSS butt joints, there are some differences among the microstructures and micro-hardness distribution, especially in the CGHAZ. For TMCP S690 HSS butt joints, the width of CGHAZ is smaller than RQT ones, and sudden decreasing of hardness occurs in TMCP S690 butt joints instead of gentle decrease in RQT ones. That means the high temperature and cooling rate have different impact on the two kinds of HSS. Hence, the numerical model using material property of RQT S690 HSS cannot reflect the mechanical performance of TMCP S690 HSS butt joints. Based on this consideration, the verification models of TMCP joints are not established in this chapter.

The material property used in coupon model is totally same with the full joint model. Furthermore, since it is difficult to record the exact cross section shape and area of each welding pass in the experiments, the shape of welding pass is assumed to be

quadrilateral in the finite element models, as shown in **Figure 5-14**. The number of welding pass for butt joint is same with the tested one, as presented in **Figure 4-2**.

(a) BJ8-3.2, BJ8-4.0 and BJ8-5.0

(b) BJ12-3.2 and BJ12-5.0

(c) BJ16-3.2

(d) BJ16-4.0

(e) BJ16-5.0

Figure 5-14 Welding pass configuration of RQT S690 HSS butt joint verification models. Moreover, since the width of simplified mode is different with the real situation, the convection and radiation surface should be adjusted to ensure the analysis reasonable. Therefore, convection and radiation of the surfaces perpendicular to welding direction are removed, and the corresponding thermal boundary is shown in **Figure 5-15**.

Figure 5-15 Convection and radiation surfaces defined in simplified model

After analysis of the verification model, comparison between numerical results and experimental ones, including temperature history, failure mode and stress-strain curves, is carried out to certify the reliability and accuracy of modelling method. The comparison of temperature history curves is to demonstrate the accuracy of thermal analysis model, and comparison of stress-strain curves is employed to show the reliability of stress analysis model.

5.5 Verification of Numerical Model

5.5.1 Welding thermal cycles

Welding process induces heat into S690 HSS butt joint, and it changes mechanical property of HAZ. According to the material property investigation in chapter 3, the strength of RQT S690 HSS is sensitive to high temperature and cooling rate, especially in the condition of peak temperature higher than 600 °C. Therefore, the accuracy of thermal analysis result directly determines the reliability of following stress analysis. **Figure 5-16** shows comparison of temperature history curves between test results and numerical ones. The numerical temperature history curves are obtained from simplified models.

(b) BJ8-4.0

(c) BJ8-5.0

(d) BJ12-3.2

(e) BJ12-5.0

(f) BJ16-3.2

(g) BJ16-4.0

(h) BJ16-5.0

Figure 5-16 Comparison of temperature history curves of S690 HSS butt joints from experimental and numerical results

Table 5-1. Welding thermal cycle information of RQT S690 HSS butt joints at 5 mm position from experiments and simplified verification models

Joint	Pass number	Welding heat input per pass(kJ/mm)	Test- T_p (°C)	Num- T_p (°C)	Test- $\Delta t_{8/5}$ (s)	Num- $\Delta t_{8/5}$ (s)
BJ8-3.2	1	1.13	472.9	480.7	-	-
	2	1.33	505.6	505.4	-	-
	3	1.17	774.1	769.3	-	-
	4	1.36	428.9	402.7	-	-
BJ8-4.0	1	1.37	464.0	491.1	-	-
	2	1.50	501.5	488.1	-	-
	3	1.65	816.5	829.4	39.2	45.9
	4	1.81	481.7	452.3	-	-
BJ8-5.0	1	1.37	515.1	553.0	-	-
	2	1.54	494.2	521.4	-	-
	3	1.62	936.1	884.1	34.0	40.2
	4	1.43	430.2	435.4	-	-
BJ12-3.2	1	1.26	266.6	278.2	-	-
	2	1.35	502.2	489.3	-	-
	3	1.31	504.1	471.9	-	-
	4	1.36	373.3	353.7	-	-
	5	1.31	576.9	558.6	-	-

CHAPTER 5 NUMERICAL INVESTIGATION OF WELDING IMPACT ON HSS BUTT
JOINT

	6	1.31	447.6	470.3	-	-
	7	1.27	398.8	396.2	-	-
BJ12-5.0	1	1.20	260.7	274.0	-	-
	2	1.50	323.4	308.5	-	-
	3	2.16	510.9	499.3	-	-
	4	1.80	459.7	447.6	-	-
	5	1.74	899.6	902.3	30.7	30.7
	6	1.35	456.2	483.4	-	-
	7	1.44	402.1	393.8	-	-
BJ16-3.2	1	1.01	192.6	193.1	-	-
	2	1.26	306.2	330.3	-	-
	3	1.24	336.4	334.4	-	-
	4	1.07	311.0	300.5	-	-
	5	1.08	386.7	386.8	-	-
	6	1.29	342.6	336.3	-	-
	7	1.04	450.5	450.0	-	-
	8	1.00	380.9	371.9	-	-
	9	1.07	360.4	343.7	-	-
	10	1.18	551.0	547.0	-	-
	11	1.26	383.2	395.4	-	-
	12	1.19	352.5	348.9	-	-
	13	1.21	848.9	854.9	12.6	18.1
	14	1.22	419.5	432.8	-	-
	15	1.08	337.4	358.4	-	-
	16	1.11	309.2	328.6	-	-
BJ16-4.0	1	1.18	188.3	194.0	-	-
	2	2.04	296.7	308.8	-	-
	3	1.78	407.1	424.9	-	-
	4	1.82	349.1	335.7	-	-
	5	1.53	421.2	409.0	-	-
	6	1.41	361.2	353.5	-	-
	7	1.43	486.0	482.1	-	-
	8	1.44	361.7	373.6	-	-
	9	1.93	906.2	922.2	22.6	30.5
	10	1.60	387.1	443.3	-	-
	11	1.41	329.1	373.1	-	-
BJ16-5.0	1	1.12	181.3	189.1	-	-
	2	2.00	288.4	282.1	-	-
	3	2.54	448.3	454.1	-	-
	4	1.86	488.2	482.8	-	-
	5	1.56	416.7	411.1	-	-
	6	1.44	498.0	488.8	-	-
	7	1.36	406.1	407.8	-	-
	8	1.99	936.2	945.6	26.0	32.1
	9	1.88	445.2	454.9	-	-
	10	1.69	383.5	389.1	-	-

In **Figure 5-16**, the distances 5 mm and 10 mm refer to the distances between the measured points to the bevel edge of weld at top surface. For the curves obtained in experimental study, the two points are located at middle of butt joint, as shown in **Figure 4-1**. While, for the numerical models, they are at the middle of coupon model. By comparing the temperature history curves, conclusion can be drawn that the numerical results are in good accordance with the experimental ones, especially in the aspects of peak temperature and cooling rate, as listed in **Table 5-1**. For the whole temperature history curves, there is still a little difference between numerical and experimental curves. It mainly caused by the constant convection ($25\text{W}/(\text{m}^2 \cdot ^\circ\text{C})$) and radiation coefficients 0.5 used in the numerical model. In reality, the convection and radiation coefficients are affected by the temperature of steel plate and environmental conditions, such as room temperature and wind. However, the difference in whole curves is acceptable, and it has little effect on the definition of mechanical property in stress analysis model since the material property in HAZ is mainly controlled by peak temperature and cooling rate. From this perspective, the proposed thermal analysis model can reflect the welding thermal cycles of butt joint accurately.

5.5.2 Failure mode

The failure positions of all tested S690 HSS butt joints are within the HAZ due to the deteriorated mechanical property caused by microstructure transformation during welding process. The failure mode of butt joints directly reveals the welding influence on S690 HSS butt joint. The comparison of the failure modes can prove the reasonability of stress analysis.

The comparison of failure modes between experimental and numerical results is presented in **Figure 5-17**. All the failure positions of FE models are within HAZ located at one side of weld, which are same with the experimental ones. That means the material property changes in HAZ, and strength of corresponding area is weaker compared with weld and base material for the uniform cross section. Therefore, the proposed stress analysis model is capable of studying the welding influence on tensile behaviour of S690 HSS butt joints.

(a) BJ8-3.2

(b) BJ8-4.0

(c) BJ8-5.0

(d) BJ12-3.2

(e) BJ12-5.0

(f) BJ16-3.2

(g) BJ16-4.0

Figure 5-17 Failure mode comparison of experimental and numerical results

5.5.3 Stress-strain curves

Although the comparison of failure mode indicates the reasonability of stress analysis model, the accuracy of model is still needed to verify in order to conduct further investigation. Hence, the stress-strain curves obtained in experimental study of butt joints are employed to compared with numerical results illustrated in **Figure 5-18**, together with ones of control coupons. The characteristic strengths gained from test and numerical analysis, including yield strength and ultimate tensile strength, are listed in **Table 5-2**.

(a) Control coupon

(b) BJ8-3.2

(c) BJ8-4.0

(d) BJ8-5.0

(e) BJ12-3.2

(f) BJ12-5.0

(g) BJ16-3.2

(h) BJ16-4.0

(i) BJ16-5.0

Figure 5-18 Comparison of stress-strain curves of S690 HSS butt joints from experimental and numerical results

Table 5-2. Characteristic strength of RQT S690 HSS butt joints from experimental and numerical results

Specimen	Test- E (GPa)	Num- E (GPa)	Test- f_y (MPa)	Num- f_y (MPa)	Error of f_y (%)	Test- f_u (MPa)	Num- f_u (MPa)	Error of f_u (%)
BJ8-3.2	211.2	200.3	603.4	546.1	9.5	730.6	727.9	0.4
BJ8-4.0	209.3	200.1	542.9	506.9	6.6	686.6	702.1	2.3
BJ8-5.0	207.5	199.8	544.2	520.2	4.4	708.7	706.8	0.3
BJ12-3.2	209.9	199.3	589.8	561.5	4.8	733.0	744.8	1.6
BJ12-5.0	206.0	198.2	552.4	528.1	4.4	698.0	729.5	4.5
BJ16-3.2	215.4	205.7	641.9	608.3	5.2	772.9	765.2	1.0
BJ16-4.0	212.2	202.4	608.5	553.4	9.1	744.6	748.3	0.5
BJ16-5.0	217.1	200.4	572.5	539.5	5.8	720.5	739.0	2.6

From the comparison of stress-strain curves of RQT S690 HSS butt joints from experiment and numerical analysis, it can be concluded that the numerical results agree well with experimental ones, although there is some difference at the beginning of plastic stage and the difference becomes more serious with increase of plate thickness. The difference is mainly caused by two reasons. One is the temperature error existing in thermal analysis which leads to less accurate material definition in stress model. The other is insufficient data of the material property of RQT S690 HSS after cooling from high temperature with different cooling rates. Generally, the peak temperature of the CGHAZ could reach 1350 °C. Nevertheless, in material property study, the highest peak temperature is only 950 °C. In the butt joint welded with thicker plate, the size of FGHAZ is reduced and the proportion of CGHAZ in HAZ is increased due to the faster cooling rate. However, in numerical model, the absence of corresponding material property in the enlarged CGHAZ of S690 HSS butt joint directly leads to lower accuracy of the derived numerical stress-strain curves. If the material property of CGHAZ can be obtained by test and defined in numerical model, the accuracy of the proposed simulation method can be further improved. In the aspect of characteristic strength, the ultimate tensile strength of FE model is more accurate compared with yield strength. The error of yield strength varies from 4.4 % to 9.5 %, and the tensile strength error is only about 0.3 % - 2.6 %. Therefore, it can be concluded that the proposed simulation method is capable of predicting the tensile behaviour of welded RQT S690 HSS butt joint accurately.

5.6 Conclusions

In this chapter, a new simulation method to estimate the tensile behaviour of S690 HSS butt joint is proposed and verified based on the experimental study results. Verification models are built with sequentially coupled thermal-stress analysis method which is composed of thermal analysis and stress analysis. The heat resource and welding process are defined in subroutine DFLUX. The material deterioration is achieved in HAZ by using subroutine USDFLD and UEXPAN according to the highest temperature and cooling rate which obtained from material property study in chapter 3. A full butt joint model is built with same dimensions of tested 8 mm S690 HSS butt joint. However, the corresponding analysis time is quite long due to the large number of elements. A simplified coupon model is then proposed to reduce computing time. Based on the simplified simulation method, eight RQT S690 HSS butt joint models are built and verified by comparing with the experimental results, including temperature history curve of butt joint during welding, failure mode and stress-strain curves. According to the analyzing results, conclusions can be obtained as follows:

- (1) The simplified coupon model can achieve almost same results with full joint model, although the temperature in full model is slightly lower and the corresponding ultimate strength is a little higher compared with coupon model. The slight difference is mainly caused by difference of volume and surface area in full model and coupon mode. However, the difference is quite small and is totally acceptable especially under the premise of drastically reduced analysis time.
- (2) By comparing the temperature history curves, it can be observed that the numerical results agree well with the experimental ones, especially in the aspect of peak temperature and cooling rate. For the whole temperature history curves, there is still a little difference between numerical and experimental curves since convection and radiation coefficients are assumed to be constant in model. However, the difference in whole curves is acceptable, and it has little effect on the definition of mechanical property in stress

analysis model since the material property in HAZ is mainly controlled by peak temperature and cooling rate. From this perspective, the proposed thermal analysis model can reflect the welding thermal cycles of butt joint accurately.

- (3) The failure positions of numerical models are in HAZ located at one side of weld which are same with the experimental ones. That means the material property changes in HAZ, and strength of corresponding area is weaker compared with weld and base material for the uniform cross section. Therefore, it can be concluded that the stress analysis model is reasonable to investigate the welding influence on tensile behaviour of S690 HSS butt joint.
- (4) From the comparison of stress-strain curves of RQT S690 HSS butt joints from experiment and numerical analysis, the numerical results agree well with experimental ones, although there is some difference at the beginning of plastic stage. The difference is mainly caused by two reasons. One is the temperature error existing in thermal analysis which leads to less accurate material definition in stress model. The other is the material property defined in stress model is non-continuous with change of peak temperature and cooling rate, where only several peak temperatures and cooling rates are considered in model. In the aspect of characteristic strength, the ultimate tensile strength of FE model is more accurate compared with yield strength. The error of yield strength varies from 4.4 % to 9.5 %, and the tensile strength error is only about 0.3 % - 2.6 %.
- (5) Based on comparison of temperature history curves and stress-strain curves, it can be concluded that the proposed simulation method can predict the tensile behaviour of welded RQT S690 HSS butt joint accurately.

CHAPTER 6

INFLUENCE OF COOLING RATE ON TENSILE PERFORMANCE OF HSS BUTT JOINTS

6.1 Introduction

The material property study of S690 HSS in chapter 3 reveals the strength of quenched and tempered HSS is affected by the peak temperature and cooling rate. The experimental results show that, in general, for a given peak temperature, the mechanical performance of S690 HSS is improved as cooling rate increases (decrease of the cooling time $\Delta t_{8/5}/\Delta t_{6/4}$). Furthermore, the influence of cooling rate on strength of S690 HSS butt joints are not the same at different peak temperatures. In terms of fabrication speed concern, higher heat input is preferred as this could lead to a better working efficiency. However, higher welding heat input is almost accompanied with higher peak temperature. As results, if the cooling rate near the HZA is not properly controlled, welding could reduce the tensile performance of S690 HSS butt joint. In order to avoid this unfavorable outcome, the cooling rate during the welding should be properly controlled to ensure the strength of the join is stronger than the connected components.

Under rapid cooling condition, the strength of welded S690 HSS butt joints will be possible to satisfy the mechanical requirement. Experimental study is the most direct way to obtain the critical cooling rate, but not the most efficient way. The proposed simulation method in chapter 5 provides a feasible way to investigate the influence of cooling rate on the tensile behaviour of S690 HSS butt joints.

In this chapter, a series of numerical models are built with the same welding heat inputs employed in the testing RQT S690 HSS butt joints. It is preliminary

investigation, and therefore it does not correspond to any physical cooling method in reality. All the models adopt the welding parameters used in experiments (including welding heat input and number of welding passes), but the cooling times $\Delta t_{8/5}$ are changed to different values of 10 s, 20 s, 30 s, 40 s, 50 s, and 60 s by directly define the field 3 value in subroutine USDFLD. In this way, the peak temperature and HAZ size of parameter models are same with the verification models, and the only difference exists in cooling rate. The failure mode, stress-strain curves and corresponding characteristic strengths are then retrieved from the numerical models. From the results of the parametric study, the variation of characteristic strengths with the cooling rate are summarized and analysed. An equation is proposed to estimate the necessary critical cooling rate such that the RQT S690 HSS butt joints could satisfy the minimum strength requirement.

6.2 Numerical Model Information

Based on the geometric parameters and welding information of RQT S690 HSS butt joints in experimental study, a total of 48 models are built with different cooling rates by using the verified simulation method. The models are built based on the assumption that the welding procedures are same with the ones used in experimental study, and the cooling time $\Delta t_{8/5}$ is directly defined as 10 s, 20 s, 30 s, 40 s, 50 s, and 60 s. That means the same welding parameters of RQT S690 HSS butt joints in tests, including the welding heat input and number of welding passes (listed in **Table 4-3**), are employed in the parametric study models. In, this way, the peak temperature and HAZ size of parameter models are same with the verification models, but the cooling rate is different. The cooling times $\Delta t_{8/5}$ with values of 10 s, 20 s, 30 s, 40 s, 50 s, and 60 s are directly defined in field 3. The cooling times $\Delta t_{6/4}$, which decrease or increase with $\Delta t_{8/5}$ proportionally for the peak temperatures of nodes lower than 800 °C, are defined in field 2 in subroutine USDFLD. In this method, the cooling rates of nodes in HAZ are same, although the peak temperatures are not constant in this area. The detailed process showing the material definition is demonstrated in APPENDIX A. The 48 numerical models are named with “NBJ(plate thickness)-(electrode diameter)- $\Delta t_{8/5}$ ”, and the detailed $\Delta t_{8/5}$ information is listed in **Table 6-1**.

Table 6-1 $\Delta t_{8/5}$ of parametric study models

Plate thickness (mm)	Model	Average heat input (kJ/mm)	$\Delta t_{8/5}$ (s)
8	NBJ8-3.2-10	1.25	10
	NBJ8-3.2-20		20
	NBJ8-3.2-30		30
	NBJ8-3.2-40		40
	NBJ8-3.2-50		50
	NBJ8-3.2-60		60
	NBJ8-4.0-10	1.58	10
	NBJ8-4.0-20		20
	NBJ8-4.0-30		30
	NBJ8-4.0-40		40
	NBJ8-4.0-50		50
	NBJ8-4.0-60		60
	NBJ8-5.0-10	1.49	10
	NBJ8-5.0-20		20
	NBJ8-5.0-30		30
	NBJ8-5.0-40		40
	NBJ8-5.0-50		50
	NBJ8-5.0-60		60
12	NBJ12-3.2-10	1.31	10
	NBJ12-3.2-20		20
	NBJ12-3.2-30		30
	NBJ12-3.2-40		40
	NBJ12-3.2-50		50
	NBJ12-3.2-60		60
	NBJ12-5.0-10	1.60	10
	NBJ12-5.0-20		20
	NBJ12-5.0-30		30
	NBJ12-5.0-40		40
	NBJ12-5.0-50		50
	NBJ12-5.0-60		60
16	NBJ16-3.2-10	1.14	10
	NBJ16-3.2-20		20
	NBJ16-3.2-30		30
	NBJ16-3.2-40		40
	NBJ16-3.2-50		50
	NBJ16-3.2-60		60
	NBJ16-4.0-10	1.60	10
	NBJ16-4.0-20		20
	NBJ16-4.0-30		30
	NBJ16-4.0-40		40
	NBJ16-4.0-50		50
	NBJ16-4.0-60		60
	NBJ16-5.0-10	1.74	10
	NBJ16-5.0-20		20
	NBJ16-5.0-30		30
	NBJ16-5.0-40		40

	NBJ16-5.0-50		50
	NBJ16-5.0-60		60

DC3D8 (an 8-node linear heat transfer brick) is chosen in thermal analysis model, and C3D8 element is employed in coupon test modelling. The mesh and boundary condition of models are also same with verification model, as shown in **Figure 5-6** and 5-13. The ambient temperature is assigned as 31°C for thermal analysis model. The thermal boundary consists of convection and radiation with the coefficients 25W/(m²·°C) and 0.5, respectively. In stress analysis model, both ends of coupon are fixed in welding procedure, and then displacement load is applied on one end of coupon to simulate the tensile procedure.

6.3 Numerical Results

6.3.1 Failure mode

After analysis of parametric study models, the failure modes, stress-strain curves and corresponding characteristic strengths are summarized to study the influence of cooling rate on the tensile behaviour of S690 HSS butt joints. The failure modes of NBJ12-3.2 series models are presented in **Figure 6-1**. Similar failure configurations and effects of changing cooling rate are also observed for other butt joints with different plate thickness. The full set of all modelling failure configurations are given in APPENDIX B. The failure position moves from base material to HAZ with increase of cooling time $\Delta t_{8/5}$, and the failure just occurs near weld when the cooling rate is low enough.

(f) NBJ12-3.2-60

Figure 6-1 Failure modes of parametric study models

The change of failure position with cooling rate is mainly caused by the material property change in the HAZ. Under faster cooling condition, such as $\Delta t_{8/5}=10$ s, the mechanical property of HAZ is stronger than base material according to material property study in chapter 3. Therefore, the failure position occurs in base material. With increase of cooling $\Delta t_{8/5}$, the material property of HAZ becomes lower. When cooling time $\Delta t_{8/5}$ is long enough, the mechanical property of HAZ becomes lower compared with base material. In this condition, the welded S690 HSS butt joint fails in HAZ near weld. Afterwards, the fail mode does not change anymore with increase of $\Delta t_{8/5}$.

6.3.2 Stress-strain curves

Besides the failure modes of numerical models, the stress-strain curves are also gained from tensile test simulations, as demonstrated in **Figure 6-2**.

(a) NBJ8-3.2-10, -20, -30, -40, -50 and -60

(b) NBJ8-4.0-10, -20, -30, -40, -50 and -60

(c) NBJ8-5.0-10, -20, -30, -40, -50 and -60

(d) NBJ12-3.2-10, -20, -30, -40, -50 and -60

(e) NBJ12-5.0-10, -20, -30, -40, -50 and -60

(f) NBJ16-3.2-10, -20, -30, -40, -50 and -60

(g) NBJ16-4.0-10, -20, -30, -40, -50 and -60

(h) NBJ16-5.0-10, -20, -30, -40, -50 and -60

Figure 6-2 Stress-strain curves of numerical models in parametric study

It can be concluded from the stress-strain curves that the strength of S690 HSS butt joint decreases with increase of cooling time $\Delta t_{8/5}$. Detailed analysis shows that the cooling rate has more serious impact on yield strength compared with ultimate tensile strength of welded HSS butt joints. Under the same cooling rate, higher welding heat input leads to lower strength for S690 HSS butt joint with same plate thickness. Additionally, the strain at ultimate tensile strength also increases for the joint with longer cooling time $\Delta t_{8/5}$. It mainly caused by the increase of ductility of S690 HSS after cooling from high temperature, especially when the cooling rate is slow as presented in material property study in chapter 3.

6.3.3 Characteristic strength

The characteristic strength of S690 HSS butt joint models includes yield strength f_y (strength at 0.2% plastic strain) and ultimate tensile strength f_u , which are summarized from the stress-strain curves illustrated in **Figure 6-2**. The characteristic strength values and corresponding reduction factors symbolled with R_y and R_u are listed in

Table 6-2. The relationship between reduction factors (R_y and R_u) and $\Delta t_{8/5}$ is presented in **Figure 6-3** and **6-4**.

Table 6-2 Characteristic strength of numerical models

Specimen	f_y (MPa)	R_y	f_u (MPa)	R_u
RQT S690 HSS	745.2	1.00	837.8	1.00
NBJ8-3.2-10	728.1	0.98	845.8	1.01
NBJ8-3.2-20	695.9	0.93	843.4	1.01
NBJ8-3.2-30	677.7	0.91	839.7	1.00
NBJ8-3.2-40	644.4	0.86	805.7	0.96
NBJ8-3.2-50	598.8	0.80	773.7	0.92
NBJ8-3.2-60	587.9	0.79	762.8	0.91
NBJ8-4.0-10	724.8	0.97	843.1	1.01
NBJ8-4.0-20	685.5	0.92	839.2	1.00
NBJ8-4.0-30	665.1	0.89	835.5	1.00
NBJ8-4.0-40	625.1	0.84	796.5	0.95
NBJ8-4.0-50	566.7	0.76	757.8	0.90
NBJ8-4.0-60	554.4	0.74	742.8	0.89
NBJ8-5.0-10	729.0	0.98	844.2	1.01
NBJ8-5.0-20	689.1	0.92	840.1	1.00
NBJ8-5.0-30	668.2	0.90	836.3	1.00
NBJ8-5.0-40	628.1	0.84	796.1	0.95
NBJ8-5.0-50	569.8	0.76	756.6	0.90
NBJ8-5.0-60	557.4	0.75	741.2	0.88
NBJ12-3.2-10	729.8	0.98	848.0	1.01
NBJ12-3.2-20	703.3	0.94	847.9	1.01
NBJ12-3.2-30	684.3	0.92	845.3	1.01
NBJ12-3.2-40	656.1	0.88	814.7	0.97
NBJ12-3.2-50	616.7	0.83	788.5	0.94
NBJ12-3.2-60	607.1	0.81	781.0	0.93
NBJ12-5.0-10	719.7	0.96	844.7	1.01
NBJ12-5.0-20	688.2	0.91	841.0	1.00
NBJ12-5.0-30	670.5	0.89	837.0	1.00
NBJ12-5.0-40	636.7	0.85	802.5	0.96
NBJ12-5.0-50	586.5	0.78	775.2	0.93
NBJ12-5.0-60	575.7	0.76	767.3	0.92
NBJ16-3.2-10	728.7	0.98	848.0	1.01
NBJ16-3.2-20	706.0	0.95	847.9	1.01
NBJ16-3.2-30	685.0	0.92	846.2	1.01
NBJ16-3.2-40	658.0	0.88	819.4	0.98
NBJ16-3.2-50	621.9	0.83	797.1	0.95
NBJ16-3.2-60	613.9	0.82	791.2	0.94
NBJ16-4.0-10	721.1	0.97	847.8	1.01
NBJ16-4.0-20	696.6	0.93	846.2	1.01
NBJ16-4.0-30	673.7	0.90	843.5	1.01
NBJ16-4.0-40	640.5	0.86	812.2	0.97
NBJ16-4.0-50	596.7	0.80	786.7	0.94

NBJ16-4.0-60	587.0	0.79	778.8	0.93
NBJ16-5.0-10	718.4	0.96	847.9	1.01
NBJ16-5.0-20	692.0	0.93	846.6	1.01
NBJ16-5.0-30	674.8	0.91	844.3	1.01
NBJ16-5.0-40	633.7	0.85	812.7	0.97
NBJ16-5.0-50	586.7	0.79	786.2	0.94
NBJ16-5.0-60	576.1	0.77	777.7	0.93

(a) NBJ8-3.2, -4.0 and -5.0

(b) NBJ12-3.2 and -5.0

(c) NBJ16-3.2, -4.0 and -5.0

Figure 6-3 Relationship between R_y and $\Delta t_{8/5}$

(a) NBJ8-3.2, -4.0 and -5.0

(b) NBJ12-3.2 and -5.0

(c) NBJ16-3.2, -4.0 and -5.0

Figure 6-4 Relationship between R_u and $\Delta t_{8/5}$

Combining the analysis on failure modes of numerical models, the mechanical performance of S690 HSS butt joint is not affected in the condition of cooling time $\Delta t_{8/5}$ below 10 s, since the failure position is in base material. With the $\Delta t_{8/5}$ increasing from 10 s to 50 s, the yield strength of butt joint deteriorates seriously. For the models with $\Delta t_{8/5}$ longer than 50 s, the deterioration becomes gentle. While, for ultimate tensile strength, it is less affected by the cooling rate compared with yield strength and only begins to decrease when $\Delta t_{8/5}$ is longer than 30 s. Additionally, with increase of welding heat input, the cooling rate has stronger influence on the strength of welded S690 HSS butt joint due to worse material property and wider HAZ area.

Besides the influence on strength of S690 HSS butt joints, the cooling rate also has effect on the residual stress of joints induced by welding. The parametric study results indicate that the residual stress decreases with increase of cooling time $\Delta t_{8/5}$. The residual stress distributions of NBJ12-5.0-10 and NBJ12-5.0-60 are presented in

Figure 6-5. The maximum principal stress in NBJ12-5.0-10 is 643.8 MPa. While, for NBJ12-5.0-60, the maximum principal stress is 564.5 MPa.

(a) NBJ12-5.0-10

(b) NBJ12-5.0-60

Figure 6-5 Residual stress distribution of NBJ12-5.0-10 and NBJ12-5.0-60

For S690 HSS, the yield strength should be with minimum value 690 MPa. Among the analysed numerical models, the joints with cooling time equalled to 10 s satisfy the mechanical requirement because these joints fail in base material. While, for other welded HSS joints, the critical cooling time $\Delta t_{8/5,c}$, which ensures the S690 HSS butt joint having the minimum yield strength 690 MPa, is located in the range of 10 s to 30 s. During welding procedure, if the cooling time $\Delta t_{8/5}$ can be controlled shorter than $\Delta t_{8/5,c}$, the yield strength of butt joint should be higher than 690 MPa. Hence, it

is quite necessary and meaningful to find out the critical cooling time $\Delta t_{8/5,c}$ for the S690 HSS butt joints.

6.4 Cooling Rate Formula

In practice, the cooling time $\Delta t_{8/5}$ is an important parameter for welded S690 HSS butt joint, since it could significantly affect the strength of the joints. Therefore, a formula is proposed to calculate the cooling time $\Delta t_{8/5}$. According to the experimental and numerical investigation, several conclusions can be obtained. Firstly, the thicker plate results in better heat conduction which directly decreases the cooling time $\Delta t_{8/5}$. Secondly, then higher welding heat input is adopted for certain thickness butt joint, the cooling time generally becomes longer. Thirdly, the loss of yield strength becomes more series in the condition of welded S690 HSS butt joint cooled with slow rate. Based on these conclusions, the formula of cooling time $\Delta t_{8/5}$ is then established with the values of welding-pass number n_w , average welding heat input q_w , plate thickness t_p and reduction factor of yield strength R_y , as shown in equation (6-1).

$$\Delta t_{8/5} = \frac{a_0}{t_p^{b_0}} (n_w q_w)^{c_0} (1 - R_y)^{d_0} + e_0 \quad (6-1)$$

where, the coefficients a_0 , b_0 , c_0 , d_0 , and e_0 are 80.2308, -0.6438, -0.3050, 0.8042, and -0.2964, respectively.

(a) NBJ8-3.2, -4.0 and -5.0

(b) NBJ12-3.2 and -5.0

(c) NBJ16-3.2, -4.0 and -5.0

Figure 6-6 Comparison of calculated $\Delta t_{8/5}$ - R_y curves and numerical ones

The curves of $\Delta t_{8/5}$ - R_y are then drawn as presented in **Figure 6-6** based on the equation (6-1) to verify its accuracy. From the comparison between calculated cooling time $\Delta t_{8/5}$ and numerical ones, it can be obtained that the standard error of proposed formula is 3.86. Overall, the proposed formula can be used to estimate cooling time $\Delta t_{8/5}$ for the S690 HSS butt joint with plate thickness increasing from 8 mm to 16 mm and welding heat input changing from 1.14 kJ/mm to 1.74 kJ/mm.

Additionally, the cooling time $\Delta t_{8/5}$ formula can also be used to obtain the critical cooling time $\Delta t_{8/5,c}$ to improve the welding process of S690 HSS butt joints for satisfying the minimum yield strength requirement 690 MPa under the premise of S690 HSS butt joint welded by SMAW. Based on the formula, if the yield strength of tested S690 HSS butt joint is aimed to reach 690 MPa, the cooling time $\Delta t_{8/5}$ should be shorter than the values listed in **Table 6-3**.

Table 6-3 Calculated critical cooling time $\Delta t_{8/5,c}$ of tested S690 HSS butt joints

Specimen	t_p (mm)	n_w	q_w (kJ/mm)	R_y	$\Delta t_{8/5,c}$ (s)
BJ8-3.2	8	4	1.25	0.926	22.78

BJ8-4.0	8	4	1.58	0.926	21.19
BJ8-5.0	8	4	1.49	0.926	21.58
BJ12-3.2	12	7	1.31	0.926	24.60
BJ12-5.0	12	7	1.60	0.926	23.13
BJ16-3.2	16	16	1.14	0.926	24.00
BJ16-4.0	16	11	1.60	0.926	24.27
BJ16-5.0	16	10	1.74	0.926	24.36

Compared with the measured cooling time $\Delta t_{8/5}$ in **Table 4-3**, the calculated $\Delta t_{8/5,c}$ of BJ8-3.2 and BJ16-3.2 are longer, but the yield strengths of tested two joints are still lower than 690 MPa. The reason is that the measured point is located on the top surface of plate, and the heat loss is faster by convection, radiation and conduction compared with the positions in plate where only conduction helps reduce the temperature. While, in order to reach the minimum yield strength requirement, the cooling time $\Delta t_{8/5}$ of every point in plate should be shorter than $\Delta t_{8/5,c}$. Additionally, since the higher welding heat input leads to higher peak temperature and larger HAZ area, the shorter $\Delta t_{8/5,c}$ is required to eliminate this influence. In the condition of joint welded with same welding heat input, the required $\Delta t_{8/5,c}$ becomes longer for the thicker plate, because the thicker plate contributes heat transfer and leads to lower peak temperature and small HAZ area. Therefore, it can be concluded that thick plate and low heat input can help S690 HSS butt joint get better mechanical performance, and the minimum strength requirement can be achieved with the premise of cooling time shorter than $\Delta t_{8/5,c}$.

6.5 Conclusions

This chapter reports numerical parametric study of cooling rate influence on the tensile performance of S690 HSS butt joints based on the verified simulation method in chapter 5. Total 48 models are built and adopt same welding parameters of tested RQT S690 HSS butt joints (including welding heat input and number of welding passes), but the cooling rates $\Delta t_{8/5}$ are defined with different values of 10 s, 20 s, 30 s, 40 s, 50 s, and 60 s. Since it is preliminary parametric study, there is no corresponding cooling method in practical application to achieve the constant cooling time in HAZ. The failure mode, stress-strain curves and corresponding characteristic strength are revealed for the numerical models. The variation trend of characteristic

strength with cooling rate are also indicated. In the end, formulations are proposed to calculate the critical cooling rate for RQT S690 HSS butt joints with plate thickness ranging from 8 mm to 16 mm to satisfy the mechanical requirement. By analysing the obtained results, conclusions are summarized as follows:

- (1) The failure position of analyzed S690 HSS butt joint moves from base material to HAZ with increase of cooling time $\Delta t_{8/5}$, and the failure just occurs near weld when the cooling rate is low enough. The change of failure position with cooling rate is mainly caused by the material property change in HAZ. Under faster cooling condition, the mechanical property of HAZ is stronger than base material. While, with increase of cooling time $\Delta t_{8/5}$, the material property of HAZ becomes lower. When cooling time $\Delta t_{8/5}$ is long enough, the welded S690 HSS butt joint fails in HAZ near weld. Afterwards, the fail mode does not change anymore with increase of $\Delta t_{8/5}$.
- (2) The mechanical performance of S690 HSS butt joint is almost not affected in the condition of cooling time $\Delta t_{8/5}$ below 10 s, since the failure position is in base material. When the $\Delta t_{8/5}$ increases from 10 s to 50 s, the yield strength of butt joint deteriorates seriously. For the models with $\Delta t_{8/5}$ longer than 50 s, the deterioration becomes gentle. While, for ultimate tensile strength, it is less affected by the cooling rate compared with yield strength and only begins to decrease in the condition of $\Delta t_{8/5}$ longer than 30 s.
- (3) A formula is proposed to calculate the cooling time $\Delta t_{8/5}$ based on the value of welding heat input, number of welding passes, plate thickness and reduction factor of yield strength. The standard error of proposed formula is 3.86. The proposed formula can be used to estimate cooling time $\Delta t_{8/5}$ for the S690 HSS butt joint with thickness ranging from 8 mm and 16 mm and welding heat input changing from 1.14 kJ/mm to 1.74 kJ/mm. Additionally, the proposed formula can also be used to obtain the critical cooling time $\Delta t_{8/5,c}$ to improve the welding process of S690 HSS butt joint for satisfying yield strength requirement 690 MPa.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Introduction

In this study, the welding influence on S690 HSS butt joint is investigated by experiments and numerical analysis. In order to achieve the intended investigation purposes, the whole study is divided into four parts, including material property study of S690 HSS after cooling from different peak temperatures with different rates, experimental study of welding influence on S690 HSS butt joints, numerical simulation of welding influence and its corresponding verification, and parametric study of cooling rate influence on the tensile behaviour of S690 HSS butt joints.

In the first part of investigation, mechanical property of S690 HSS after cooling from different peak temperatures with different cooling rates is tested. A new setup is designed to heat and cool the specimen. Verification test is carried out to make sure the setup could heat and cool the coupon uniformly. The specimens are heated up to 600°C, 700°C, 800°C, 900°C and 950°C, and then cooled down with different rates by blowing air. The gained stress-strain curves are classified by peak temperature and cooling rate. The obtained material properties will be employed in numerical simulation to define the mechanical behaviour of HAZ.

In the experimental study of welding influence on S690 HSS butt joints, eleven butt joints are fabricated by using 8 mm, 12 mm, 16 mm and 22 mm thickness plates. The 8 mm, 12 mm and 16 mm plates are delivered by reheated, quenched and tempered (RQT) process, and 22 mm plate is fabricated by thermo-mechanically controlled process (TMCP). Shielded Metal Arc Welding is used in tests together with different diameter electrodes for the purpose of achieving different welding heat inputs. After

the welding process is completed and the welded joint is cooled down, two coupons are machined out. Standard direct tensile tests are then carried out to investigate the impacts of welding on S690 HSS butt joints. Furthermore, microstructure inspections and micro-hardness tests are conducted to map the location, size and the mechanical properties of the HAZ.

In numerical simulation of welding process and tensile test of S690 HSS butt joints, a new simulation method is proposed with inhomogeneous material property defined in HAZ. The numerical models are built with sequentially coupled thermal-stress analysis method which consists of thermal analysis and stress analysis. The heat resource and welding process are defined in subroutine DFLUX. The material deterioration in HAZ, classified by peak temperature and cooling rate, is achieved by using subroutines USDFLD and UEXPAN. Eight RQT S690 HSS butt joint models are built and analyzed, and verification is conducted by comparing the temperature history curves, failure modes and stress-strain curves of butt joints with the experimental ones.

In the numerical parametric study, a series of numerical models are built with same welding heat inputs of tested RQT S690 HSS butt joints based on the verified simulation method. All the models adopt the welding parameters in experiments (including welding heat input and number of welding passes), but the cooling rates $\Delta t_{8/5}$ are defined with different values of 10 s, 20 s, 30 s, 40 s, 50 s, and 60 s. The failure mode, stress-strain curves and corresponding characteristic strength are revealed for the numerical models. The variation trend of characteristic strength with cooling rate are also indicated. In the end, a formulation is proposed to calculate the critical cooling rate to ensure the RQT S690 HSS butt joints satisfy the minimum mechanical requirement.

7.2 Conclusions

7.2.1 Material property of S690 HSS in HAZ

Both the peak temperature and cooling rate have effects on the mechanical performance of S690 HSS after cooling from high temperatures. It is mainly caused by the microstructure transformation from tempered martensite to bainite, ferrite,

pearlite or cementite during heating and cooling process. Under the same peak temperature, the mechanical performance of S690 HSS is improved as the cooling rate increases (decrease of cooling time $\Delta t_{8/5}/\Delta t_{6/4}$). Furthermore, the influence of cooling rate on strength of S690 HSS becomes stronger with the peak temperature ranging from 950 °C to 800 °C, and then got weaker with the continuous reduction of peak temperature from 800 °C to 600 °C.

The mechanical property of S690 HSS can recover to or even be higher than the original strength after heating and cooling process in the condition of peak temperature above 800 °C and short cooling time $\Delta t_{8/5}$, such as 15 s. While, when the cooling time $\Delta t_{8/5}$ is long enough, the deterioration of material property becomes stable for the coupons heated above 800 °C, and the strength is generally lower compared with original one. In the condition of peak temperature decreasing from 700 °C to 600 °C, the strength of S690 HSS gradually recovered to original value.

The ductility of S690 HSS after heating also changes with cooling rate. With increase of cooling rate, the ductility of post-heated S690 HSS decreases. In the condition of relatively low cooling rate, the ductility is improved compared with original material. On the other hand, once the cooling rate is high enough, the ductility becomes worse than the original one. The critical cooling rate is not fixed, and it changes with peak temperature.

7.2.2 Welding influence on S690 HSS butt joints

The light optical microscopy and SEM images reveal that, after welding of RQT S690 HSS, the tempered martensite of base material is transformed to granular bainite in the CGHAZ and to ferrite and cementite in the FGHAZ. For the tempering zone further away from the weld, some of the tempered martensite are decomposed to ferrite. For TMCP S690 HSS, the main difference from RQT HSS is that the area of CGHAZ is quite small, and its microstructure is not the granular bainite. This variation in CGHAZ of TMCP S690 HSS butt joint is generally good for the toughness and ductility of welded HSS joints.

The micro-hardness tests confirm that the HAZ width increases as welding heat input is increased. While, in the condition of similar welding heating input, the HAZ size decreases with increase of plate thickness.

Tensile tests show that all S690 HSS butt joints tested have lower yield strength than the original HSS base material. In addition, they all fracture within the HAZ with lower strength and worse ductility. Further analysis reveals that for a given plate thickness, both the yield strength and the tensile strength reduction factors decrease with increase of welding heat input. However, for a similar level of welding heat input, the both reduction factors increase as the plate thickness increases. The reduction factor of yield strength R_y ranges from 0.73 to 0.86 while the reduction factor of ultimate tensile strength varying from 0.82 to 0.92 for tested RQT S690 HSS butt joints. On the other hand, for TMCP S690 HSS butt joints, the reduction factor of yield strength R_y ranges from 0.74 to 0.83 while the reduction factor of tensile strength R_u varying from 0.87 to 0.92.

7.2.3 Numerical simulation of welding influence on S690 HSS butt joints

In the simulation of welding influence on S690 HSS butt joints, sequentially coupled thermal-stress analysis method provided in ABAQUS can truly reproduce the welding process and following tensile tests. Simplified coupon models could save lots of analyzing time and get almost same results with full butt joint models, and therefore are employed to certify the accuracy of the simulation method.

The temperature history curves obtained from thermal analysis model agree well with the ones gained from experimental study, especially in the aspect of peak temperature and cooling rate. It proves the accuracy of thermal analysis model. All the stress analysis models fail within HAZ, which are same with the tested butt joints. That means the material property changing program defined in subroutines UEXPAN and USDFLD work in the stress analysis model, and therefore the reasonability of verification model is indicated. The comparison of stress-strain curves of RQT S690 HSS butt joints from experiments and numerical analysis reveal that the numerical results agree well with experimental ones. In the aspect of characteristic strength, the

ultimate tensile strength of FE model is more accurate compared with yield strength. The error of yield strength varies from 4.4 % to 9.5 %, and the tensile strength error is only about 0.4 % - 2.6 %. All these prove the proposed simulation method is capable of estimating the tensile behaviour of welded RQT S690 HSS butt joint accurately.

7.2.4 Influence of cooling rate on tensile behaviour of S690 HSS butt joints

The influence of cooling rate on mechanical behaviour of S690 HSS butt joints mainly reflect in two aspects in terms of failure mode and strength deterioration. The failure position of analyzed S690 HSS butt joints moves from base material to HAZ with increase of cooling time $\Delta t_{8/5}$, and the mechanical performance of S690 HSS butt joints decreases if cooling time $\Delta t_{8/5}$ is extended. Compared with tensile strength, deterioration of yield strength of S690 HSS butt joints becomes more serious as cooling time $\Delta t_{8/5}$ increases.

Additionally, on the basis of parametric study results, a cooling time $\Delta t_{8/5}$ formula is proposed to according to the value of welding heat input q_w , number of welding passes n_w , plate thickness t_p and reduction factor of yield strength R_y . The standard error of proposed formula is 3.86. The proposed formula can be used to estimate cooling time $\Delta t_{8/5}$ for the welded S690 HSS butt joint with thickness ranging from 8 mm and 16 mm and welding heat input changing from 1.14 kJ/mm to 1.74 kJ/mm. Additionally, this formula can also be used to obtain the critical cooling time $\Delta t_{8/5,c}$ to improve the welding process of S690 HSS butt joint for satisfying yield strength requirement 690 MPa.

7.3 FUTURE WORK

In this study, the material property of HAZ is investigated, and only several selected peak temperatures and cooling rates are chosen. The highest peak temperature is 950 °C, but the temperature in CGHAZ during welding may exceed 1350 °C. In the aspect of cooling rate, due to the limitation of cooling setup, the cooling rate cannot

be controlled exactly and only several cooling rates are considered in tests. In this condition, the material property of HAZ cannot be described and reflected accurately. Therefore, it is essential to conduct further investigation to supplement the experimental data with higher peak temperatures and more different cooling rates.

For the experimental study of welding influence on mechanical performance of S690 HSS butt joint, SMAW is adopted in this study and different diameter electrodes are employed to gain different welding heat inputs. However, the disadvantage of using SMAW is the welding speed cannot be controlled same for each welding pass. In the next stage of this investigation, flux cored arc welding (FCAW) and submerged arc welding (SAW) will be carried out by welding robot, so that the welding speed and welding heat input can be controlled exactly. Additionally, the welding speed will be taken as one important factor since it will affect the deposition rate of weld and cooling rate of joint. Furthermore, thicker S690 HSS plate will be used to fully understand the welding impact on the butt joint strength.

In the aspect of parametric study, only the influence of cooling rate on S690 HSS butt joint is considered to improve the mechanical performance of welded joints. However, there are still some other ways to solve the problem of strength deterioration, such as reducing the welding heat input. Additionally, on the basis of the experimental results, the welding influence on the strength of joint becomes weak with increase of plate thickness. Hence, it is meaningful to conduct further parametric study to reveal the relationship between reduction factor of characteristic strength and welding heat input or plate thickness, so that welding impact on strength of S690 HSS butt joint can be eliminated.

REFERENCES

- [1]. ABAQUS U.S.M., 2012. Version 6.12. Dassault Systemes Simulia Corp, Rhode Island, USA.
- [2]. Adnan C., 2009. Effect of cooling rate on hardness and microstructure of AISI 1020, AISI 1040 and AISI 1060 Steels. *International journal of Physical sciences*, 4(9): 514-518.
- [3]. AISC. 2010. Specification for structural steel buildings, *AISC*, Chicago, American Institute of Steel Construction.
- [4]. Akselsen O.M., Rorvik G., Onsoien M.I., Grong O., 1989. Assessment and predictions of HAZ tensile properties of high-strength steels. *Welding Journal*, 68(9): 356.
- [5]. ASTM, 2009. Standard specification for high-yield-strength, quenched and tempered alloy steel plate, suitable for welding. ASTM International, West Conshohocken, United States.
- [6]. ASTM E92-17, 2017. Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials, ASTM International, West Conshohocken, PA.
- [7]. AWS, 2008. Structural Welding Code steel. Miami, American National Standards Institute.
- [8]. Ban H., Shi G., 2018. Overall buckling behaviour and design of high-strength steel welded section columns. *Journal of Constructional Steel Research*, 143: 180-195.
- [9]. Barani A.A., Li F., Romano P., Ponge D., Raabe D., 2007. Design of high-strength steels by microalloying and thermomechanical treatment. *Materials Science and Engineering: A*, 463(1-2): 138-146.

- [10]. Baudin T., Quesne C., Jura J., Penelle R., 2001. Microstructural characterization in a hot-rolled, two-phase steel. *Materials characterization*, 47(5): 365-373.
- [11]. Beg D., Hladnik L., 1996. Slenderness limit of class 3 I cross-sections made of high strength steel. *Journal of Constructional Steel Research*, 38(3): 201-217.
- [12]. Bhadeshia H.K.D.H., Honeycombe R.W.K., 2006. Steels-Microstructures and Properties, 3rd edition, Butterworth-Heinmann, Oxford, UK.
- [13]. Bhole S., Nemade J., Collins L., Liu C., 2006. Effect of nickel and molybdenum additions on weld metal toughness in a submerged arc welded HSLA line-pipe steel. *Journal of Materials Processing Technology*, 173(1): 92-100.
- [14]. Błacha S., Węglowski M.S., Dymek S. and Kopuścianiński M., 2016. Microstructural characterization and mechanical properties of electron beam welded joint of high strength steel grade S690QL. *Archives of Metallurgy and Materials*, 61(2): 1193-1200.
- [15]. Bonifaz E.A., 2000. Finite element analysis of heat flow in single-pass arc welds. *WELDING JOURNAL-NEW YORK-*, 79(5): 121-s.
- [16]. Boumerzoug Z., Derfouf C., Baudin T., 2010. Effect of welding on microstructure and mechanical properties of an industrial low carbon steel. *Engineering*, 2(07): 502-506.
- [17]. Brickstad B., Josefson B., 1998. A parametric study of residual stresses in multi-pass butt-welded stainless steel pipes. *International Journal of Pressure Vessels and Piping*, 75(1): 11-25.
- [18]. BSI, 2001. BS EN 10002-1: tensile testing of metallic materials: part1 method of test at ambient temperature, ed. London: British Standards Institution.
- [19]. BSI, 2003. BS EN ISO 18265: Metallic materials. Conversion of hardness values, International Organization for Standardization, Geneva.
- [20]. BSI, 2004. Hot rolled products of structural steels: part 4 technical delivery conditions for thermomechanical rolled weldable fine grain structural steels, *BS EN 10025-4*. British Standards Institution, London.

- [21]. BSI, 2009. Hot rolled products of structural steels: part 6 technical delivery conditions for flat products of high yield strength structural steels in the quenched and tempered condition, *BS EN 10025-6*. British Standards Institution, London.
- [22]. BSI, 2005a. Eurocode 3: Design of steel structures: part 1-2. General rules- structural fire design, *BS EN 1993-1-2*. London: British Standard Institution.
- [23]. BSI, 2005b. Eurocode 3: Design of steel structures: part 1-12: Additional rules for the extension of EN 1993 up to steel grades S700, *BS EN 1993-1-12*. London, British Standard Institution.
- [24]. BSI, 2005c. Eurocode 3: Design of Steel Structures. Part 1-8: Design of joints, *BS EN 1993-1-2*. London: British Standard Institution.
- [25]. BSI, 2005d. 6507-1: Metallic Materials-Vickers Hardness Test- Part 1: Test Method, British Standards Institution, London.
- [26]. BSI, 2009. EN BS. 1011-1: Welding. Recommendations for welding of metallic materials. General guidance for arc welding.
- [27]. Cahoon J., Broughton W.H., Kutzak A., 1971. The determination of yield strength from hardness measurements. *Metallurgical Transactions*, 2(7): 1979-1983.
- [28]. Chen C., Chiew S.P., Zhao M.S., Lee C.K., Fung T.C., 2019. Welding effect on tensile strength of grade S690Q steel butt joint. *Journal of constructional steel research*, 153: 153-168.
- [29]. Chen C., Zhang X.Z., Zhao M.S., Lee C.K., Fung T.C., Chiew S.P., 2017. Effects of welding on the tensile performance of high strength steel T-stub joints. *Structures*. Elsevier, 9: 70-78.
- [30]. Chen J., Young B., Uy B., 2006. Behaviour of high strength structural steel at elevated temperatures. *Journal of structural engineering*, 132(12): 1948-1954.
- [31]. Chen J.H., Kikuta Y., Araki T., Yoneda M., Matsuda Y., 1984. Micro-fracture behaviour induced by MA constituent (Island Martensite) in simulated welding heat affected zone of HT80 high strength low alloyed steel. *Acta Metallurgica*, 32(10): 1779-1788.

- [32]. Chiew S.P., Zhao M.S., Lee C.K., 2014. Mechanical properties of heat-treated high strength steel under fire/post-fire conditions. *Journal of Constructional Steel Research*, 98: 12-19.
- [33]. Choi I.R., Chung K.S., Kim D.H., 2014. Thermal and mechanical properties of high-strength structural steel HSA800 at elevated temperatures. *Materials & Design*, 63: 544-551.
- [34]. Clatterbuck D.M., Chrzan D.C., Morris Jr J.W., 2002. The inherent tensile strength of iron, *Philosophical Magazine Letters* 82: 141–147.
- [35]. Coelho A.M.G., Bijlaard F.S., 2007. Experimental behaviour of high strength steel end-plate connections. *Journal of Constructional Steel Research*, 63(9): 1228-1240.
- [36]. Coelho A.M.G., Bijlaard F.S., Gresnigt N., Da Silva L.S., 2004. Experimental assessment of the behaviour of bolted T-stub connections made up of welded plates. *Journal of Constructional Steel Research*, 60(2): 269-311.
- [37]. Coelho A.M.G., Bijlaard F.S., Da Silva L.S., 2004. Experimental assessment of the ductility of extended end plate connections. *Engineering Structures*, 26(9): 1185-1206.
- [38]. Coelho A.M.G., Bijlaard F.S., Kolstein H., 2009. Experimental behaviour of high-strength steel web shear panels. *Engineering Structures*, 31(7): 1543-1555.
- [39]. Coelho A.M.G., Da Silva L.S., Bijlaard F.S., 2004. Characterization of the nonlinear behaviour of single bolted T-stub connections. *Connections in Steel Structures V*, Amsterdam, The Netherlands.
- [40]. Cui B., Peng Y., Zhao L., Peng M., An T. and Ma C., 2016. Effect of heat input on microstructure and toughness of coarse grained heat affected zone of Q890 steel. *ISIJ International*, 56(1): 132-139.
- [41]. De Meester B., 1997. The weldability of modern structural TMCP steels. *ISIJ international*, 37(6): 537-551.

- [42]. Deng D., 2009. FEM prediction of welding residual stress and distortion in carbon steel considering phase transformation effects. *Materials & Design*, 30(2): 359-366.
- [43]. Deng D., Murakawa H., 2006. Numerical simulation of temperature field and residual stress in multi-pass welds in stainless steel pipe and comparison with experimental measurements. *Computational materials science*, 37(3): 269-277.
- [44]. Dixon B., Hakansson K., 1995. Effects of welding parameters on weld zone toughness and hardness in 690 MPa steel. *Welding journal*, 74(4): 122s-132s.
- [45]. Gao L., Sun H.C., Jin F.N., Fan H.L., 2009. Load-carrying capacity of high-strength steel box-sections I: Stub columns. *Journal of Constructional Steel Research*, 65: 918–924.
- [46]. Gao M., Zeng X., Hu Q., Yan J., 2009. Laser-TIG hybrid welding of ultra-fine-grained steel. *Journal of materials processing technology*, 209(2): 785-791.
- [47]. Garcia-Mateo C., Peet M., Caballero F.G. and Bhadeshia H.K.D.H., 2004. Tempering of hard mixture of bainitic ferrite and austenite. *Materials Science and Technology*, 20(7): 814-818.
- [48]. Gladman T., 1996. The Physical Metallurgy of Microalloyed Steels, IOM Communications, London.
- [49]. Gery D., Long H., Maropoulos P., 2005. Effects of welding speed, energy input and heat source distribution on temperature variations in butt joint welding. *Journal of materials processing technology*, 167(2-3): 393-401.
- [50]. Gibson S.L., 2013. Individual emergency preparedness in Canada: Widening the lens on the social environment. University of Ottawa (Canada).
- [51]. Goldak J., Chakravarti A., Bibby M.A., 1984. New finite element model for welding heat sources. *Metallurgical transactions B*, 15(2): 299-305.
- [52]. Guimarães J.R.C., Rios P.R., 2013. Modeling lath martensite transformation curve. *Metallurgical and Materials Transactions A*, 44(1): 2-4.

- [53]. Guo W., Crowther D., Francis J.A., Thompson A., Liu Z., Li L., 2015. Microstructure and mechanical properties of laser welded S960 high strength steel. *Materials & Design*, 2015, 85: 534-548.
- [54]. Guo Z., Kim Y.H., 2001. The limits of strength and toughness in steel. *ISIJ international*, 41(6): 599-611.
- [55]. Hochhauser D.I.F., Rauch M.R., 2012. Influence of the soft zone on the strength of welded modern HSLA steels. *Welding in the World*, 56(5-6): 77-85.
- [56]. Hume-Rothery W., 1966. The Structures of Alloys of Iron, Pergamon Press, Oxford, UK.
- [57]. Jiao H., Zhao X.L., Lau A., 2015. Hardness and compressive capacity of longitudinally welded very high strength steel tubes. *Journal of Constructional Steel Research*, 114: 405-416.
- [58]. Kaplan D., Murry G., 2008a. Thermal, Metallurgical and Mechanical Phenomena in the Heat Affected Zone. Kokoken, USA, John Wiley & Sons.
- [59]. Kaplan D., Murry G., 2008b. Thermal, Metallurgical and Mechanical Phenomena in the Heat Affected Zone. *Metallurgy and Mechanics of Welding: Processes and Industrial Applications*, 89-131.
- [60]. Kapustka N., Conrardy C., Babu S., Albright C., 2008. Effect of GMAW process and material conditions on DP 780 and TRIP 780 welds. *WELDING JOURNAL-NEW YORK*-, 87(6): 135.
- [61]. Khan M.I., Biro E., Zhou Y., 2008a. Microstructure and mechanical properties of resistance spot welded advanced high strength steels. *Materials Transactions*, 49(7): 1629-1637.
- [62]. Khan M.I., Kuntz M.L., Zhou Y., 2008b. Effects of weld microstructure on static and impact performance of resistance spot welded joints in advanced high strength steels. *Science and Technology of Welding and Joining*, 13(3): 294-304.
- [63]. Khurshid M., Barsoum Z., Barsoum I., 2015. Load Carrying Capacities of Butt Welded Joints in High Strength Steels. *Journal of Engineering Materials and Technology*, 137(4): 041003.

- [64]. Kim D.K., Lee C.H., Han K.H., Kim J.H., Lee S.E., Sim H.B., 2014. Strength and residual stress evaluation of stub columns fabricated from 800 MPa high-strength steel. *Journal of Constructional Steel Research*, 102: 111-120.
- [65]. Klein M., Spindler H., Luger A., Rauch R., Stiaszny P., Eigelsberger M., 2005. Thermomechanically Hot Rolled High and Ultra High Strength Steel Grades—Processing, *Properties and Application*, 500: 543-550.
- [66]. Koistinen D.P., Marburger R.E., 1959. A general equation prescribing the extent of the austenite-martensite transformation in pure iron-carbon alloys and plain carbon steels, *Acta Metallurgica*, 7: 59–60.
- [67]. Koo J.Y., 1987. Welding metallurgy of structural steels. *JOM*, 39(6): 31-35.
- [68]. Kou S., 2003. Welding metallurgy. John Wiley & Sons.
- [69]. Lan L, Qiu C, Zhao D, Gao X., Du L., 2011. Microstructural characteristics and toughness of the simulated coarse grained heat affected zone of high strength low carbon bainitic steel. *Materials Science and Engineering: A*, 529: 192-200.
- [70]. Lambert-Perlade A, Gourgues A.F., Besson J., Sturel T., Pineau A., 2004. Mechanisms and modeling of cleavage fracture in simulated heat-affected zone microstructures of a high-strength low alloy steel. *Metallurgical and Materials Transactions A*, 35(13): 1039-1053.
- [71]. Lambert-Perlade A., Gourgues A.F., Pineau A., 2004. Austenite to bainite phase transformation in the heat-affected zone of a high strength low alloy steel. *Acta Materialia*, 52(8): 2337-2348.
- [72]. Layus P., Kah P., Khlusova E., Orlov V., 2018. Study of the sensitivity of high-strength cold-resistant shipbuilding steels to thermal cycle of arc welding. *International Journal of Mechanical and Materials Engineering*, 13(1), 3.
- [73]. Lee C.H., Han K.H., Uang C.M., Kim D.K., Park C.H., Kim J.H., 2012. Flexural strength and rotation capacity of I-shaped beams fabricated from 800-MPa steel. *Journal of Structural Engineering*, 139(6): 1043-1058.

- [74]. Lee J.H., Mahendran M., Makelainen P., 2003. Prediction of mechanical properties of light gauge steels at elevated temperatures. *Journal of Constructional Steel Research*, 59:1517-32.
- [75]. Lee S., Kim B.C., Lee D.Y., 1989. Fracture mechanism in coarse grained HAZ of HSLA steel welds. *Scripta metallurgica*, 23(6): 995-1000.
- [76]. Lee S.J., Lee Y.K., 2008. Finite element simulation of quench distortion in a low-alloy steel incorporating transformation kinetics. *Acta Materialia*, 56(7): 1482-1490.
- [77]. Lee S.J., Van Tyne C.J., 2012. A kinetics model for martensite transformation in plain carbon and low-alloyed steels. *Metallurgical and Materials Transactions A*, 43(2): 422-427.
- [78]. Linnert G.E., 1967. *Welding Metallurgy*. Miami, Florida, USA, American Welding Society. Volume 2, Technology.
- [79]. Li T.J., Li G.Q., Chan S.L., Wang Y.B., 2016. Behaviour of Q690 high-strength steel columns: Part 1: Experimental investigation. *Journal of Constructional Steel Research*, 123: 18-30.
- [80]. Li Y., 2001. The effect of vanadium and niobium on the properties and microstructure of the intercritically reheated coarse grained heat affected zone in low carbon microalloyed steels. *ISIJ international*, 41(1): 46-55.
- [81]. Loureiro A.J.R., 2002. Effect of heat input on plastic deformation of undermatched welds. *Journal of materials processing technology*, 128(1): 240-249.
- [82]. Ma T.Y., Liu X., Hu Y.F., Chung K.F., Li G.Q., 2018. Structural behaviour of slender columns of high strength S690 steel welded H-sections under compression. *Engineering Structures*, 157: 75-85.
- [83]. Messler Jr R.W., 2008. *Principles of welding: processes, physics, chemistry, and metallurgy*: John Wiley & Sons.

- [84]. Miki C., Homma K., Tominaga T., 2002. High strength and high performance steels and their use in bridge structures. *Journal of Constructional Steel Research*, 58(1): 3-20.
- [85]. Mochizuki M., Shintomi T., Hashimoto Y., Toyoda M., 2004. Analytical study on deformation and strength in HAZ-softened welded joints of fine-grained steels. *Welding in the World*, 48(9-10): 2-12.
- [86]. Mohandas T., Reddy G.M., Kumar B.S., 1999, Heat-affected zone softening in high-strength low-alloy steels. *Journal of Materials Processing Technology*, 88(1-3): 284-294.
- [87]. Movahed P., Kolahgar S., Marashi S.P.H., Pouranvari M., Parvin N., 2009. The effect of intercritical heat treatment temperature on the tensile properties and work hardening behaviour of ferrite–martensite dual phase steel sheets. *Materials Science and Engineering: A*, 518(1-2): 1-6.
- [88]. Može P., Beg D., 2010. High strength steel tension splices with one or two bolts. *Journal of Constructional Steel Research*, 66(8): 1000-1010.
- [89]. Može P., Beg D., Lopatič J., 2007. Net cross-section design resistance and local ductility of elements made of high strength steel. *Journal of Constructional Steel Research*, 63(11): 1431-1441.
- [90]. Ohtani H., Terasaki F., Kunitake T., 1982. The microstructure and toughness of high tensile strength steels. *Tetsu-to-Hagané*, 58(3): 434-451.
- [91]. Oikawa H., Murayama G., Sakiyama T., Takahashi, Y., Ishikawa, T., 2006. Resistance spot weldability of high strength steel (HSS) sheets for automobile. *Shinnittetsu Giho*, 385: 36.
- [92]. Olawale A.O., Plank R.J., 1988. The collapse analysis of steel columns in fire using a finite strip method. *International Journal for Numerical Methods in Engineering*, 26(17):2755-64.
- [93]. Outinen J., 1999. Mechanical properties of structural steels at elevated temperatures. Licentiate thesis, Helsinki University of Technology, Finland.

- [94]. Pavlina E., Van Tyne C., 2008. Correlation of yield strength and tensile strength with hardness for steels. *Journal of Materials Engineering and Performance*, 17(6): 888-893.
- [95]. Pavlina E.J., Van Tyne C.J., 2008. Correlation of yield strength and tensile strength with hardness for steels. *Journal of materials engineering and performance*, 17(6): 888-893.
- [96]. Pirinen M., Martikainen Y., Layus P.D., Karkhin V.A., Ivanov S.Y., 2016. Effect of heat input on the mechanical properties of welded joints in high-strength steels. *Welding International*, 30(2): 129-132.
- [97]. Qiang X., Bijlaard F.S., Kolstein H., 2012a. Dependence of mechanical properties of high strength steel S690 on elevated temperatures. *Construction and Building Materials*, 30: 73-79.
- [98]. Qiang X., Bijlaard F.S., Kolstein H., 2012b. Post-fire mechanical properties of high strength structural steels S460 and S690. *Engineering Structures*, 35: 1-10.
- [99]. Raoul J., 2005. Use and application of high-performance steels for steel structures. Iabse.
- [100]. Rasmussen K.J.R., Hancock G.J., 1992. Plate slenderness limits for high strength steel sections. *Journal of Constructional Steel Research*, 23(1-3): 73-96.
- [101]. Ricles J.M., Sause R., Green P.S., 1998. High-strength steel: implications of material and geometric characteristics on inelastic flexural behaviour. *Engineering Structures*, 20(4-6): 323-335.
- [102]. Rodrigues D.M., Menezes L.F., Loureiro A., Fernandes J.V., 2004. Numerical study of the plastic behaviour in tension of welds in high strength steels. *International Journal of Plasticity*, 20(1): 1-18.
- [103]. Rollason E.C., 1973. Metallurg-y for engineers. London: Edward Arnold.
- [104]. Rosenthal D., 1946. The theory of moving sources of heat and its applications to metal treatments. *Transactions ASME*, 68: 849.

- [105]. Schaupp T., Schroepfer D., Kromm A., and Kannengiesser T., 2017. Welding residual stresses in 960 MPa grade QT and TMCP high-strength steels. *Journal of Manufacturing Processes*, 27: 226-232.
- [106]. Shamass R., Cashell K.A., 2017. Behaviour of Composite Beams Made Using High Strength Steel, *Structures*. Elsevier, 12: 88-101.
- [107]. Shi G., Ban H., Bijlaard F.S., 2012. Tests and numerical study of ultra-high strength steel columns with end restraints. *Journal of Constructional Steel Research*, 70: 236-247.
- [108]. Shi Y.W., Han Z.X., 2008. Effect of weld thermal cycle on microstructure and fracture toughness of simulated heat-affected zone for a 800 MPa grade high strength low alloy steel. *Journal of materials processing technology*, 207(1-3): 30-39.
- [109]. Śloderbach Z., Pająk J., 2015. Determination of Ranges of Components of Heat Affected Zone Including Changes of Structure/Określenie Zakresów Składowych Strefy Wpływu Ciepła Uwzględniając Zmiany Struktury. *Archives of Metallurgy and Materials*, 60(4): 2607-2612.
- [110]. Soul F., Hamdy N., 2012. Numerical Simulation of Residual Stress and Strain Behaviour After Temperature. *Welding Processes*, InTech
- [111]. Sun, Y., Liang, Y., Zhao, O., 2019. Testing, numerical modelling and design of S690 high strength steel welded I-section stub columns. *Journal of Constructional Steel Research*, 159, 521-533.
- [112]. Suzuki T., Ogawa T., Ikarashi K., 1994. A study on local buckling behavior of hybrid beams. *Thin-walled structures*, 19(2-4): 337-351.
- [113]. Sverdlin A.V., and Ness Eds A.R., 2007. Chapter 3: fundamental concepts in steel heat treatment. *Steel heat treatment handbook: metallurgy and technology*, Taylor & Francis Group.
- [114]. Swanson J.A., Leon R.T., 2000. Bolted steel connections: tests on T-stub components. *Journal of Structural Engineering*, 126(1): 50-56.

- [115]. Tamura I., Sekine H., Tanaka T., Ouchi C., 1988. Thermomechanical Processing of High-Strength Low-Alloy Steels, Butterworth & Co., London, UK.
- [116]. Tao Z., Wang X.Q., Uy B., 2012. Stress-strain curves of structural and reinforcing steels after exposure to elevated temperatures. *Journal of Materials in Civil Engineering*, 25(9): 1306-1316.
- [117]. Trahair N.S., Bradford M.A., Nethercot D.A., Gardner L., 2008. The Behaviour and Design of Steel Structures to EC3, 4th edn Spon Press, London.
- [118]. Uy B., Sloane R.J., 1998. Behaviour of composite tee beams constructed with high strength steel. *Journal of Constructional Steel Research*, 1(46): 203-204.
- [119]. Verhoeven, J.D. 2007. Steel metallurgy for the non-metallurgist. *ASM International*.
- [120]. Wang J., Gardner L., 2017. Flexural buckling of hot-finished high-strength steel SHS and RHS columns. *Journal of Structural Engineering*, 143(6): 04017028.
- [121]. Wang Y.B., Li G.Q., Chen S.W., Sun F.F., 2012. Experimental and numerical study on the behaviour of axially compressed high strength steel columns with H-section. *Engineering Structures*, 43: 149-159.
- [122]. Wang Z., Tizani W., Wang Q., 2010. Strength and initial stiffness of a blind-bolt connection based on the T-stub model. *Engineering Structures*, 32(9): 2505-2517.
- [123]. Vuherer T., Maruschak P., Samardzic I., 2012. Behaviour of coarse grain heat affected zone (HAZ) during cycle loading. *Metallurgy*, 51(3): 301-304.
- [124]. Xu W., Westerbaan D., Nayak S.S., Chen, D.L., Goodwin, F., Zhou, Y., 2013. Tensile and fatigue properties of fiber laser welded high strength low alloy and DP980 dual-phase steel joints. *Materials & Design*, 43: 373-383.
- [125]. Zhang H., Senkara J., 2011. Resistance welding: fundamentals and applications. CRC press.
- [126]. Zhang S., Zhao H., Shu F., He W., Wang G., 2017. Microstructure and Corrosion Behaviour of Simulated Welding HAZ of Q315NS Steel in Sulfuric Acid Solution. *Metals*, 7(6): 194.

- [127]. Zhang Y.Q., Zhang H.Q., Li J.F., and Liu W.M., 2019. Effect of heat input on microstructure and toughness of coarse grain heat affected zone in nb microalloyed hsla steels. *Journal of Iron and Steel Research, International*, 16(5):73-80.
- [128]. Zhao M.S., Chiew S.P., Lee C.K., 2016. Post weld heat treatment for high strength steel welded connections. *Journal of Constructional Steel Research*, 122: 167-177.
- [129]. Zhao M.S., Lee C.K., Chiew S.P., 2016. Tensile behaviour of high performance structural steel T-stub joints. *Journal of Constructional Steel Research*, 2016, 122: 316-325.
- [130]. Zhao M.S., Lee C.K., Fung T.C., Chiew S.P., 2017. Impact of welding on the strength of high performance steel T-stub joints. *Journal of Constructional Steel Research*, 131: 110-121.
- [131]. Ziemian R.D., 2010. Guide to Stability Design Criteria for Metal Structures, 6th edn John Wiley & Sons, Inc., New Jersey.

APPENDIX A

MATERIAL PROPERTY DEFINITION IN ABAQUS

For the stress-strain curves of S690Q HSS at elevated temperature, the accompanied field values are 1, 0, 0 for field 1, field 2 and field 3 as shown in **Figure A (a)**. While, the stress strain curves of S690Q HSS after cooling from different peak temperatures with different cooling rates are also defined with field values. For the peak temperature is equal to or higher than 800 °C, the values of field 1, field 2, and field 3 are 800 °C/900 °C/950 °C, 100, $\Delta t_{8/5}$, respectively, as presented in **Figure A (b)**. For the peak temperature lower than 800 °C, the values of field 1, field 2, and field 3 are 600 °C/700 °C/800 °C, $\Delta t_{6/4}$, 0, respectively, as presented in **Figure A (c)**. Then, the data base of S690Q HSS material property is established in ABAQUS. The reason why field 2 is assigned with value 100 for the stress-strain curves with peak temperatures higher than 800 °C and field 3 is assigned with value 0 for stress-strain curves with peak temperatures lower than 800 °C is to make sure the two values not to affect the linear interpolation of $\Delta t_{8/5}$ and $\Delta t_{6/4}$.

Plastic

Hardening: Isotropic

☐ Use strain-rate-dependent data

☒ Use temperature-dependent data

Number of field variables: 3

▼ Suboptions

Data

	Yield Stress	Plastic Strain	Temp	Field 1	Field 2	Field 3
1	614163100	0	30	1	0	0
2	757649567.6	0.002386801	30	1	0	0
3	791961865.9	0.004767919	30	1	0	0
4	807531600.8	0.007143381	30	1	0	0
5	815541745.6	0.009513214	30	1	0	0
6	819880480.3	0.011877443	30	1	0	0
7	852802338	0.025129844	30	1	0	0
8	878421377.6	0.038208913	30	1	0	0
9	895076443.3	0.051119126	30	1	0	0
10	736995720	0.182321557	30	1	0	0
11	604950600	0	100	1	0	0
12	726328051	0.002401798	100	1	0	0
13	762774039.5	0.004803596	100	1	0	0

(a) Stress-strain curves at elevated temperatures defined in ABAQUS

Plastic

Hardening: Isotropic

☐ Use strain-rate-dependent data

☒ Use temperature-dependent data

Number of field variables: 3

▼ Suboptions

Data

	Yield Stress	Plastic Strain	Temp	Field 1	Field 2	Field 3
418	55921126.67	0.12247388	800	800	100	9.1
419	53656037.69	0.13597388	800	800	100	9.1
420	51126026.61	0.14947388	800	800	100	9.1
421	676790951	0	30	950	100	11.3
422	826400000	0.002	30	950	100	11.3
423	911930000	0.003669192	30	950	100	11.3
424	978480000	0.005669192	30	950	100	11.3
425	1078830000	0.015669192	30	950	100	11.3
426	1128320000	0.025669192	30	950	100	11.3
427	1150790000	0.035669192	30	950	100	11.3
428	1152380000	0.040669192	30	950	100	11.3
429	1152380000	0.5	30	950	100	11.3
430	30641250	0	800	950	100	11.3

OK Cancel

(b) Stress-strain curves with peak temperatures higher than 800 °C defined in ABAQUS

Plastic

Hardening: Isotropic

☐ Use strain-rate-dependent data

☒ Use temperature-dependent data

Number of field variables: 3

▼ Suboptions

Data

	Yield Stress	Plastic Strain	Temp	Field 1	Field 2	Field 3
181	337370000	0	30	700	1.9	0
182	439320000	0.002	30	700	1.9	0
183	482710000	0.004	30	700	1.9	0
184	511360000	0.006	30	700	1.9	0
185	532710000	0.008	30	700	1.9	0
186	595670000	0.018	30	700	1.9	0
187	638610000	0.028	30	700	1.9	0
188	673880000	0.038	30	700	1.9	0
189	703870000	0.048	30	700	1.9	0
190	837690000	0.1558	30	700	1.9	0
191	837690000	0.5	30	700	1.9	0
192	30641250	0	700	700	1.9	0
193	39264485.33	0.00291969	700	700	1.9	0

OK Cancel

(c) Stress-strain curves with peak temperatures lower than 800 °C defined in ABAQUS

Figure A-1 Material property definition with field values in ABAQUS

In the subroutine UEXPAN, the peak temperature of every node is recorded for each welding pass. If the peak temperature is lower than 800 °C, the cooling time $\Delta t_{6/4}$ (time for node to cool down from 600 °C to 400 °C) will be recorded. For the node

with peak temperature higher than 800 °C, the cooling time $\Delta t_{8/5}$ (time for node to cool down from 800 °C to 500 °C) is measured. These recorded peak temperature and corresponding cooling time $\Delta t_{6/4} / \Delta t_{8/5}$ will be replaced by new ones if the following welding pass leads to higher peak temperature for the node. After the welding process completed and butt joint cooled down to ambient temperature, the field values are finally determined based on the peak temperature and the cooling time. In USDFLD, the peak temperature is then assigned to field 1. The cooling time $\Delta t_{6/4}$ is defined to field 2 in the condition of peak temperature lower than 800 °C, and the cooling time $\Delta t_{8/5}$ is assigned to field 3 when the peak temperature is higher than 800 °C. After the welding process and butt joint cooling down to ambient temperature, the field values are finally determined based on the peak temperature and the cooling time in the welding pass. Based on these values, the corresponding stress-strain curve will be calculated by linear interpolation and then chosen from the data base (stress-strain curves shown in **Figure 5-8**) and assigned to node. For example, if the peak temperature and cooling time $\Delta t_{6/4}$ of one node are 626 °C and 52 s, respectively, according to thermal analysis results, the 626 °C and 52 s will be assigned to field 1 and field 3 by subroutine USDFLD, respectively. According to the two values, the linear interpolation will be used three times to gain the corresponding stress-strain curve based on the data base of material property of S690Q HSS in ABAQUS. In the first step, the stress-strain curve with field 1 = 700 and field 2 = 33.1 and stress-strain curve with field 1 = 700 °C and field 2 = 63.1 will be interpolated linearly to gain the curve with peak temperature 700 °C and cooling time $\Delta t_{6/4}$ 52 s. In the second step, the stress-strain curve with field 1 = 600 and field 2 = 102.7 and stress-strain curve with field 1 = 700 °C and field 2 = 36.4 will be interpolated linearly to gain the curve with peak temperature 600 °C and cooling time $\Delta t_{8/5}$ 52 s. In the third step, the obtained two curves are interpolated linearly again by using the peak temperature 700 °C and 600 °C to achieve the stress-strain curves with peak temperature 626 °C and cooling time $\Delta t_{6/4}$ 52 s. For the field 3, the value is 0 for the mentioned four stress-strain curves. It will not change in interpolation, and therefore will affect the interpolation of stress-strain curves determined by field 1 (peak temperature) and field 2 (cooling time $\Delta t_{6/4}$).

While, in parametric study models, the material definition is almost same. The only difference is that the cooling time is assigned to field 2 or field 3 in subroutine USDFLD according to the thermal analysis, but defined with certain values. For example, the peak temperature and cooling time $\Delta t_{8/5}$ of the node at 5 mm away from the weld bevel in verification model for BJ8-4.0 are 829.4 °C and 45.9 s (listed in **Table 5-1**), respectively. In verification mode, the two values are assigned to field 1 and field 3, respectively, and then corresponding stress-strain curves will be obtained by linear interpolation of the defined stress-strain curves and assigned to node. While, in the parametric study models, since the all welding information is not changed at all, the thermal analysis results are totally same with the verification model. The peak temperature and cooling time $\Delta t_{8/5}$ of the node at 5 mm away from the weld bevel are still 829.4 °C and 45.9 s, respectively. In subroutine USDFLD, the peak temperature 829.4 °C is assigned to field 1, but the cooling time $\Delta t_{8/5}$ is defined as 20 s instead of 45.9 s for field 3. In this condition, the stress-strain curve with peak temperature 829.4 °C and cooling time 20 s is calculated by linear interpolation method and assigned to node. The same thing happens to other nodes in the model. The peak temperature of the node is still same with ones in verification model, but the cooling time $\Delta t_{8/5}$ just becomes 20 s. For the nodes with peak temperature lower than 800 °C, the cooling time $\Delta t_{6/4}$ decreases or increases proportionally according to $\Delta t_{8/5}$. In the case mentioned above, the cooling time $\Delta t_{8/5}$ 45.9 s decreases to 20 s, the reduction factor should be 0.436 (ratio of 20 over 45.9). Then, the $\Delta t_{6/4}$ obtained from thermal analysis will be multiplied by 0.436 and assigned to field 2. The peak temperature is assigned to field 2. Based on the two values of field 1 and 2, the stress-strain curve heated lower than 800 °C are calculated by linear interpolation and assigned to node. In this way, all the nodes which are affected by heating and cooling process have same cooling time $\Delta t_{8/5}$ 20 s for the peak temperature higher than 800 °C and same cooling time $\Delta t_{6/4} \times 0.436$ for the peak temperature lower than 800 °C.

SUBROUTINE DFLUX

SUBROUTINE

DFLUX(FLUX,SOL,KSTEP,JINC,TIME,NOEL,NPT,COORDS,JLTYP,
TEMP,PRESS,SNAME)

INCLUDE 'ABA_PARAM.INC'

PARAMETER(one=1.d0)

DIMENSION COORDS(3),FLUX(2),TIME(2)

CHARACTER*80 SNAME

CC
CC

IF((TIME(2).GE.(0.0)).and.(TIME(2).le.(t1))) THEN

x=COORDS(1) *(Spatial coordinates in x direction)*
y=COORDS(2) *(Spatial coordinates in y direction)*
z=COORDS(3) *(Spatial coordinates in z direction)*

a=a_{HF}

b=b_{HF}

c1=c_{HF2}

c2=c_{HF1}

PI=3.1415

q= $\eta * U * I$ *(Welding heat input)*
v=v *(Welding speed)*

d=v*(TIME(2)) *(Forward distance of welding heat source)*

x0= *(Coordinate x of welding heat source center)*

y0= *(Coordinate y of welding heat source center)*

z0= *(Coordinate z of welding heat source center)*

x1=(x-x0) *(Relative coordinate x of welding heat source center)*

y1=(y-y0) *(Relative coordinate y of welding heat source center)*

z1=(z-z0) *(Relative coordinate z of welding heat source center)*

IF((z1).gt.(d)) THEN *(Front part definition of heat source)*

c=c1

heat=6*sqrt(3.0)*q*1.33/(a*b*c*PI*sqrt(PI))

shape=exp(-3*(y1)**2/b**2-3*(x1)**2/a**2-3*(z1-d)**2/c**2)

JLTYP=1

FLUX(1)=heat*shape

ELSE IF((z1).le.(d)) THEN *(Rear part definition of heat source)*

c=c2

heat=6*sqrt(3.0)*q*0.67/(a*b*c*PI*sqrt(PI))

shape=exp(-3*(y1)**2/b**2-3*(x1)**2/a**2-3*(z1-d)**2/c**2)

JLTYP=1

FLUX(1)=heat*shape

END IF

END IF

CC
CCCCCCCCCCCCCCCC(Cooling Stage of Welding Pass-1)CCCCCCCCCCCCCCCCCCCC

IF((TIME(2).GE.(t1)).and.(TIME(2).le.(t2)))THEN

FLUX(1)=0

END IF

CC
CCCCCCCCCCCCCCCCCCCC(Welding Pass-2, 3, ...)CCCCCCCCCCCCCCCCCCCC

IF((TIME(2).GE.(t2)).and.(TIME(2).le.(t3)))THEN

x=COORDS(1)

(Spatial coordinates in x direction)

y=COORDS(2)

(Spatial coordinates in y direction)

z=COORDS(3)

(Spatial coordinates in z direction)

a=a_{HF}

b=b_{HF}

c1=c_{HF2}

c2=c_{HF1}

PI=3.1415

q= $\eta \cdot U \cdot I$

(Welding heat input)

v=v

(Welding speed)

d=v*(TIME(2)-t2)

(Forward distance of welding heat source)

x0=

(Coordinate x of welding heat source center)

y0=

(Coordinate y of welding heat source center)

z0=

(Coordinate z of welding heat source center)

x1=(x-x0)

(Relative coordinate x of welding heat source center)

y1=(y-y0)

(Relative coordinate y of welding heat source center)

z1=(z-z0)

(Relative coordinate z of welding heat source center)

```

IF((z1).gt.(d)) THEN                                (Front part definition of heat source)
  c=c1

```

```

  heat=6*sqrt(3.0)*q*1.33/(a*b*c*PI*sqrt(PI))
  shape=exp(-3*(y1)**2/b**2-3*(x1)**2/a**2-3*(z1-d)**2/c**2)

```

```

  JLTYP=1

```

```

  FLUX(1)=heat*shape

```

```

ELSE IF((z1).le.(d)) THEN                            (Rear part definition of heat source)
  c=c2

```

```

  heat=6*sqrt(3.0)*q*0.67/(a*b*c*PI*sqrt(PI))
  shape=exp(-3*(y1)**2/b**2-3*(x1)**2/a**2-3*(z1-d)**2/c**2)

```

```

  JLTYP=1

```

```

  FLUX(1)=heat*shape

```

```

END IF

```

```

END IF

```

```

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCC(Cooling Stage of Welding Pass-2,3,...)CCCCCCCCCCCC

```

```

IF((TIME(2).GE.(t3)).and.(TIME(2).le.(t4)))THEN

```

```

  FLUX(1)=0

```

```

END IF

```

```

.....

```

```

RETURN

```

```

END

```

SUBROUTINE UEXPAN

SUBROUTINE

UEXPAN(EXPAN,DEXPANDT,TEMP,TIME,DTIME,PREDEF,
DPRED,STATEV,CMNAME,NSTATV,NOEL)

INCLUDE 'ABA_PARAM.INC'

CHARACTER*80 CMNAME

DIMENSION EXPAN(*),DEXPANDT(*),TEMP(2),TIME(2),PREDEF(*),
DPRED(*),STATEV(NSTATV)

CC
CC(*Time Recorded at 800 °C, 600 °C, 500 °C and 400 °C during Welding Pass-1*)CC

STATEV(1)=TEMP(2)

IF (TIME(2).LT.(t2)) THEN
IF (TEMP(1).GE.STATEV(2)) THEN

TTOP1=TEMP(1)
STATEV(2)=TTOP1

END IF

IF (((TTOP1.GE.600).AND.(TTOP1.LT.800))) THEN
IF (TEMP(1).LE.0) THEN

T02=TEMP(1)-TEMP(2)

IF ((TEMP(1).LE.600).AND.(T02.GE.600)) THEN
STATEV(3)=TIME(2)+(600.0-TEMP(1)/TEMP(2)*DTIME)
END IF

IF ((TEMP(1).LE.400).AND.(T02.GE.400)) THEN
STATEV(4)=TIME(2)+(400.0-TEMP(1)/TEMP(2)*DTIME)
END IF

END IF

ELSE IF (TTOP1.GE.800) THEN
IF (TEMP(1).LE.0) THEN

T02=TEMP(1)-TEMP(2)

IF (((TEMP(1).LE.800).AND.(T02.GE.800))) THEN

STATEV(5)=TIME(2)+(800.0-TEMP(1)/TEMP(2)*DTIME)

END IF

IF ((TEMP(1).LE.500).AND.(T02.GE.500)) THEN

STATEV(6)=TIME(2)+(500.0-TEMP(1)/TEMP(2)*DTIME)

END IF

END IF

END IF

CC
C(Time Recorded at 800 °C, 600 °C, 500 °C and 400 °C during Welding Pass-2,3,...)C

ELSE IF ((TIME(2).GE.(t2)).AND.(TIME(2).LT.(t4))) THEN

IF (TEMP(1).GE.STATEV(2)) THEN

TTOP2=TEMP(1)

STATEV(2)=TTOP2

END IF

IF (((TTOP2.GE.600).AND.(TTOP2.LT.800))) THEN

IF (TEMP(1).LE.0) THEN

T02=TEMP(1)-TEMP(2)

IF ((TEMP(1).LE.600).AND.(T02.GE.600)) THEN

STATEV(3)=TIME(2)+(600.0-TEMP(1)/TEMP(2)*DTIME)

END IF

IF ((TEMP(1).LE.400).AND.(T02.GE.400)) THEN

STATEV(4)=TIME(2)+(400.0-TEMP(1)/TEMP(2)*DTIME)

END IF

END IF

ELSE IF (TTOP2.GE.800) THEN

IF (TEMP(1).LE.0) THEN

T02=TEMP(1)-TEMP(2)

IF (((TEMP(1).LE.800).AND.(T02.GE.800))) THEN

```

STATEV(5)=TIME(2)+(800.0-TEMP(1)/TEMP(2)*DTIME)

END IF

IF ((TEMP(1).LE.500).AND.(T02.GE.500)) THEN

STATEV(6)=TIME(2)+(500.0-TEMP(1)/TEMP(2)*DTIME)

END IF
END IF

END IF

.....

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCC (Expansion Coefficient of S690Q HSS)CCCCCCCCCCCC

IF (CMNAME(1:5).EQ.'STEEL') THEN
IF ((TEMP(1).GE.(20.0)).AND.(TEMP(1).LT.(750.0))) THEN

ALPHA01=(1.2E-5)*TEMP(1)+(0.4E-8)*TEMP(1)**2-2.416E-4
ALPHA02=(1.2E-5)*(TEMP(1)-TEMP(2))+(0.4E-8)*
(TEMP(1)-TEMP(2))**2-(2.416E-4)
EXPAN(1)=ALPHA01-ALPHA02
DEXPANDT(1)=(1.2E-5)+(0.8E-8)*TEMP(1)

ELSE IF ((TEMP(1).GE.(750.0)).AND.(TEMP(1).LE.(860.0))) THEN

EXPAN(1)=0
DEXPANDT(1)=0

ELSE IF ((TEMP(1).GE.(860.0)).AND.(TEMP(1).LE.(1399.0))) THEN

ALPHA01=(2.0E-5)*TEMP(1)-(6.2E-3)
ALPHA02=(2.0E-5)*(TEMP(1)-TEMP(2))-(6.2E-3)
EXPAN(1)=ALPHA01-ALPHA02
DEXPANDT(1)=2.0E-5

ELSE

EXPAN(1)=0
DEXPANDT(1)=0

END IF
END IF

```

CC
 CCCCCCCCCCCCCCCCCC(Expansion Coefficient of Weld)CCCCCCCCCCCCCCCC

IF (CMNAME(1:4).EQ.'WELD') THEN
 IF ((TEMP(1).GE.(20.0)).AND.(TEMP(1).LT.(750.0))) THEN

ALPHA01=(1.2E-5)*TEMP(1)+(0.4E-8)*TEMP(1)**2-2.416E-4
 ALPHA02=(1.2E-5)*(TEMP(1)-TEMP(2))+(0.4E-8)*
 (TEMP(1)-TEMP(2))**2-(2.416E-4)
 EXPAN(1)=ALPHA01-ALPHA02
 DEXPANDT(1)=(1.2E-5)+(0.8E-8)*TEMP(1)

ELSE IF ((TEMP(1).GE.(750.0)).AND.(TEMP(1).LE.(860.0))) THEN

EXPAN(1)=0
 DEXPANDT(1)=0

ELSE IF ((TEMP(1).GE.(860.0)).AND.(TEMP(1).LE.(1399.0))) THEN

ALPHA01=(2.0E-5)*TEMP(1)-(6.2E-3)
 ALPHA02=(2.0E-5)*(TEMP(1)-TEMP(2))-(6.2E-3)
 EXPAN(1)=ALPHA01-ALPHA02
 DEXPANDT(1)=2.0E-5

ELSE
 EXPAN(1)=0
 DEXPANDT(1)=0

END IF
 END IF

RETURN
 END

SUBROUTINE USDFLD

SUBROUTINE USDFLD(FIELD,STATEV,PNEWDT,DIRECT,T,CELENT,
 TIME,DTIME,CMNAME,ORNAME,NFIELD,NSTATV,NOEL,NPT,LAYER,
 KSPT,KSTEP,KINC,NDI,NSHR,COORD,JMAC,JMATYP,MATLAYO,LACCFL
 A)

INCLUDE 'ABA_PARAM.INC'

CHARACTER*80 CMNAME,ORNAME

CHARACTER*3 FLGRAY(15)

DIMENSION FIELD(NFIELD),STATEV(NSTATV),DIRECT(3,3),
 T(3,3),TIME(2)

DIMENSION ARRAY(15),JARRAY(15),JMAC(*),JMATYP(*),COORD(*)

TMAX=STATEV(2) *(Peak temperature of node in welding process)*

IF (STATEV(1).GT.(0.0)) THEN *(Heating stage)*

FIELD(1)=1

FIELD(2)=0

FIELD(3)=0

ELSE IF (STATEV(1).LE.(0.0)) THEN *(Cooling stage)*

IF (TMAX.LT.600) THEN

FIELD(1)=1

FIELD(2)=0

FIELD(3)=0

END IF

IF ((TMAX.GE.600).AND.(TMAX.LT.800)) THEN

(Peak temperature higher than 600 °C and less than 800 °C)

FIELD(1)=TMAX

FIELD(2)=(STATEV(4)-STATEV(3))

($\Delta t_{6/4}$)

FIELD(3)=0

END IF

IF ((TMAX.GE.800)) THEN *(Peak temperature higher than 800 °C)*

```
FIELD(1)=TMAX  
FIELD(2)=100  
FIELD(3)=STATEV(6)-STATEV(5)  $(\Delta t_{8/5})$ 
```

```
END IF  
END IF
```

```
RETURN  
END
```

215

(13) NBJ8-5.0-10

(14) NBJ8-5.0-20

(15) NBJ8-5.0-30

(16) NBJ8-5.0-40

(17) NBJ8-5.0-50

(18) NBJ8-5.0-60

(19) NBJ12-3.2-10

(20) NBJ12-3.2-20

(21) NBJ12-3.2-30

(22) NBJ12-3.2-40

(23) NBJ12-3.2-50

(24) NBJ12-3.2-60

(25) NBJ12-5.0-10

(26) NBJ12-5.0-20

(27) NBJ12-5.0-30

(28) NBJ12-5.0-40

(29) NBJ12-5.2-50

(30) NBJ12-5.2-60

(31) NBJ16-3.2-10

(32) NBJ16-3.2-20

(33) NBJ16-3.2-30

(34) NBJ16-3.2-40

(35) NBJ16-3.2-50

(36) NBJ16-3.2-60

(37) NBJ16-4.0-10

(38) NBJ16-4.0-20

(39) NBJ16-4.0-30

(40) NBJ16-4.0-40

(41) NBJ16-4.0-50

(42) NBJ16-4.0-60

(43) NBJ16-5.0-10

(44) NBJ16-5.0-20

(45) NBJ16-5.0-30

(46) NBJ16-5.0-40

(47) NBJ16-5.0-50

(48) NBJ16-5.0-60

Figure B-1 Failure modes of parametric study models