



## **Faculty of Mechanical Engineering**

# **CREEP ASSESSMENT OF OVERHEATED GRADE 9Cr STEELS FOR DECISION MAKING ON PLANT INTEGRITY**

**Ng Guat Peng**

**Doctor of Engineering**

**2014**

**CREEP ASSESSMENT OF OVERHEATED GRADE 9Cr STEELS FOR  
DECISION MAKING ON PLANT INTEGRITY**

**NG GUAT PENG**

**A thesis submitted  
In fulfillment of the requirements for the degree of Doctor of Engineering**

**Faculty of Mechanical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2014**

## DECLARATION

I declare that this thesis entitled “Creep Assessment of Overheated Grade 9-Cr Steels For Decision Making On Plant Integrity” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : .....

Name : .....

Date : .....

## **APPROVAL**

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Engineering.

Signature : .....

Name Supervisor : .....

Date : .....

## **DEDICATION**

To my beloved mother, madam Chua Nui Poey, beloved father, Mr Ng Tiow Hock,  
husband, Mr Leong Chee Kian and sons, Leong Xu En and Leong Xu Zhe.

## ABSTRACT

Alloy steels Gr. 91 (9Cr1MoVNb) and Gr.92 (9Cr0.5Mo1.8WVNb) are commonly used to construct supercritical and ultra supercritical boilers. The martensitic properties of both alloys require post weld heat treatment (PWHT) as mandatory process after welding. In the past experience at TNB power plants, overheating incidents had occurred during post weld heat treatment due to unintentional factors. The soaking temperature which is supposed to be controlled at 730°C to 770°C was accidentally overshoot to beyond  $A_{c1}$  (800°C~830°C) and  $A_{c3}$  (890°C ~ 930°C). The overheated alloys experienced microstructure transformation which would have changed the hardness property and the creep strength of the alloys, making them unfit for further service. According to standard practice, the overheated components should be replaced immediately. Nevertheless, power station management, sometimes, encounters dilemma due to lack of time allowance to extend outages for further repair work. For this reason, the re-use of overheated components on temporary basis has become an important option to protect the national interest. This research is designed with the objective to gain an understanding of the metallurgical behavior of the overheated components and develop experimental creep curves as a guideline for operational decision making on this short term solution. Prior to this, TNB Research provided advices and recommendations based on practical knowledge and experience. With the presence of this research data, TNB Research can make a better judgment with a higher confidence level in problem-solving and decision making. The main purpose of this research is to investigate the microstructure transformation and creep property change as a result of possible overshoot above the normal tempering temperature (730°C-770°C) for these steels. The experimental results show that the hardness property is dependent on the type of microstructure matrix transformed at room temperature. The creep strength is proportional to the hardness property, but inversely proportional to the applied stress. As expected, the high temperature creep strength for both overheated alloys has dropped significantly as compared to the published creep master curves for new and unexposed specimens. Both Gr 91 and Gr. 92 alloys with overheated and degraded microstructure / property can be re-used for temporary service, depending on the metal temperature and applied stress level. Soft microstructure as a result of overheating at 850°C to 900°C has a very limited creep rupture time and it was considered unfit and impractical for further service, especially at design parameters for supercritical boilers, but if the parameters are compromised to subcritical level, temporary service up to 10,000 hours is possible. Hard microstructure as a result of cooling from 900°C to 1000°C shows improvement in creep life, likely attributed to tempering effect during creep exposure. The experimental creep data/curves developed for overheated Gr. 91 and Gr. 92 steels are reasonable and they are ready to serve as a reference/guideline to determine the temporary duration and operational load/stress selection. The allowance to re-use overheated components on temporary basis would have saved the downtime. Statistics from Stesen Janakuasa Sultan Azlan Shah, Manjung, the biggest coal-fired power plant in the county shows that the economic gain or return is equivalent to a few millions Ringgit Malaysia.

## ABSTRAK

Aloi keluli gred 91 (9Cr1MoVNb) dan gred 92 (9Cr0.5Mo1.8WVNb) mempunyai rintangan suhu yang baik dan biasa diguna untuk membina dandang elektrik bertaraf 'supercritical' dan 'ultra-supercritical'. Kedua-dua jenis aloi memerlukan rawatan haba selepas kimpalan. Pengalaman yang lepas dari stesen janakuasa TNB menunjukkan kekurangan dalam pengawalan suhu, menyebabkan suhu pada logam telah melampaui  $Ac_1$  ( $800^{\circ}C \sim 830^{\circ}C$ ) dan  $Ac_3$  ( $890^{\circ}C \sim 930^{\circ}C$ ) secara tidak sengaja. Pemanasan secara berlebihan telah menyebabkan perubahan dalam sifat-sifat bahan, termasuk mikrostruktur, kekerasan, dan kekuatan rayapan aloi. Kod piawai tidak menggalakkan penggunaan semula aloi-aloi yang mengalami pemanasan secara berlebihan. Namun, pihak pengurusan stesen penjanaan kadang-kadang menghadapi dilema sebabkan tempoh hentitugas tidak dapat dipanjangkan untuk kerja-kerja penyelenggaraan lanjut. Justeru, tanpa pilihan, komponen-komponen yang mengalami pemanasan pada suhu berlebihan terpaksa diguna dalam perkhidmatan seterusnya untuk melindungi kepentingan pelanggan. Penyelidikan ini bertujuan untuk memupuk pemahaman dalam bidang kajian logam bagi aloi yang mengalami kemerosotan prestasi akibat dari pemanasan berlebihan dan membangunkan data-data rayapan sebagai panduan untuk keputusan operasi dan penyelesaian berjangka pendek. Tanpa data-data penyelidikan ini, TNB Research memberi khidmat nasihat mengikut pengetahuan dan pengalaman tanpa rujukan. Penyelidikan ini amat penting untuk mencapai penilaian teknikal yang lebih tepat dengan tahap keyakinan yang lebih tinggi. Keputusan eksperimen menunjukkan kekerasan bahan adalah ditentukan oleh jenis mikrostruktur matrik pada suhu bilik selepas pemanasan. Kekuatan rayapan adalah berkadar langsung dengan kekerasan, tetapi kerkadar songsang dengan daya tegangan. Kekuatan rayapan didapati telah menurun dengan ketara bila dibandingkan dengan data-data rayapan yang diterbitkan untuk spesimen baru. Kedua-dua aloi gred 91 dan gred 92 yang mengalami pemanasan secara berlebihan boleh dipertimbangkan untuk perkhidmatan sementara waktu, bergantung kepada suhu dan daya tegangan. Secara umum, pemanasan pada  $850^{\circ}C$  to  $900^{\circ}C$  menghasilkan mikrostruktur yang lembut, hayat komponen adalah terhad dan tidak dicadangkan untuk penggunaan seterusnya, khususnya untuk paras 'supercritical', tetapi bagi 'subcritical' pada suhu dan daya tegangan yang lebih rendah, hayat komponen adalah dalam lingkungan 10,000 jam. Pemanasan pada  $900^{\circ}C$  ke  $1000^{\circ}C$  menghasilkan mikrostruktur yang keras, hayat komponen adalah lebih panjang, mungkin disebabkan oleh kesan-kesan 'tempering' bila terdedah kepada ujian rayapan. Data-data rayapan untuk aloi 91 dan 92 daripada eksperimen penyelidikan ini didapati munasabah dan merupakan panduan atau rujukan yang amat berguna dalam penentuan tempoh perkhidmatan berjangka pendek dan pemilihan daya tegangan yang optimum. Penggunaan semula komponen-komponen yang mengalami pemanasan pada suhu berlebihan secara tidak sengaja, sebagai penyelesaian sementara waktu, telah dapat menjimatkan 'downtime'. Statistik dari Stesen Janakuasa Sultan Azlan Shah, Manjung, menunjukkan keuntungan ekonomi dalam lingkungan beberapa juta Ringgit Malaysia.

## **ACKNOWLEDGEMENT**

I wish to express my sincere appreciation to Prof. Dr. Mohd Razali bin Muhamad, my principal supervisor, for the advice, motivation, guidance, trust and support during my Engineering Doctorate Program with UTeM. I also would like to extend the appreciation to Dr. Mohd Ahadlin bin Mohd Daud, my co-supervisor for his inputs, comments and ideas given, especially during the drafting of my thesis.

My great appreciation to Dr. Badrol Ahmad, my industrial supervisor, for his continuous mentoring, supervision and encouragement during my research work. Thank you for giving me opportunity to continue learning under your mentorship even after your re-assignment to another position in TNB HQ.

I gratefully acknowledge the support from TNB and TNBR management for the funding of this research program and their consideration and assistance given to me in pursuing and achieving of this Engineering Doctorate Program on part time basis. Last, but not least, special thanks to Kementerian Pendidikan Malaysia for providing the MyPhD Industry Grant to support the tuition fee.



## TABLE OF CONTENTS

	PAGE
<b>DECLARATION</b>	<b>i</b>
<b>APPROVAL</b>	<b>ii</b>
<b>DEDICATION</b>	<b>iii</b>
<b>ABSTRACT</b>	<b>iv</b>
<b>ABSTRAK</b>	<b>v</b>
<b>ACKNOWLEDGEMENTS</b>	<b>vi</b>
<b>TABLE OF CONTENTS</b>	<b>vii</b>
<b>LIST OF TABLES</b>	<b>xi</b>
<b>LIST OF FIGURES</b>	<b>xii</b>
<b>LIST OF ABBREVIATIONS</b>	<b>xix</b>
<b>LIST OF SYMBOLS</b>	<b>xxii</b>
<b>LIST OF APPENDICES</b>	<b>xxiv</b>
<b>LIST OF PUBLICATIONS</b>	<b>xxv</b>
<b>CHAPTER</b>	
<b>1. INTRODUCTION</b>	<b>1</b>
1.1 Background	1
1.2 Problem statement	5
1.3 Research Objective	7
1.4 Research methodology	8
1.5 Research Scope	10
1.6 Significance of research	12
1.7 Layout of thesis	12
<b>2. LITERATURE REVIEW</b>	
2.1 Evolution of 9-12 Cr steels	14
2.2 Metallurgy	16
2.2.1 Effect of alloying elements on modified 9Cr-1Mo ferritic steels	18
2.2.2 Continuous cooling transformation (CCT) diagram	24
2.2.2.1 Transformation behavior of Gr. 91 and Gr. 92 steels	26

2.2.3	Martensitic transformation	28
2.2.4	Heat treatment	29
2.2.5	Characteristics of precipitates	34
2.2.6	Strengthening mechanism	43
2.3	Welding	45
2.3.1	Post weld heat treatment	45
2.3.2	Microstructural features of welds	46
2.3.2.1	Heat-affected zone (HAZ)	47
2.3.2.2	Weld metal (WM)	48
2.4	Creep property of 9-12% chromium creep resistant steels	49
2.4.1	Creep definition and fundamentals	49
2.4.2	Measurement of creep properties	52
2.4.2.1	Stress rupture testing	52
2.4.2.2	Creep testing	53
2.4.2.3	Constant stress creep testing	54
2.4.3	Creep-curve description	54
2.4.4	Diffusional creep	58
2.4.4.1	Nabarro-Herring creep	59
2.4.4.2	Coble creep	59
2.4.5	Dislocation creep	59
2.4.5.1	Work hardening and recovery	60
2.4.5.2	Internal stress	61
2.4.6	Evolution of microstructure and material properties during creep	61
2.4.6.1	Precipitates	61
2.4.6.2	Recovery of martensite and dislocations	65
2.4.6.3	Softening / hardness	67
2.4.7	Creep fracture	69
2.4.7.1	Type IV cracking in ICHAZ	73

2.4.7.2	Type I weld metal failure	75
2.4.7.3	Type IIIa weld interface failure	76
2.4.7.4	Inter-bead boundary creep failure (weld bead to weld bead)	80
2.4.8	Prediction of creep life using Larson Miller Parameter (LMP)	82
2.5	Summary	83
<b>3.</b>	<b>MATERIALS AND METHODS</b>	<b>84</b>
3.1	Materials selection and preparation	84
3.2	Experimental work on heat treatment	86
3.3	Metallography	92
3.3.1	Optical microscopy (OM)	92
3.3.2	Scanning electron microscope (SEM)	94
3.3.3	Micro-hardness measurement	94
3.3.4	Transmission electron microscope (TEM)	96
3.3.4.1	Preparation of thin foils	96
3.3.4.2	Image analysis	97
3.4	Uninterrupted creep rupture testing	98
3.5	Summary	102
<b>4.</b>	<b>EXPERIMENTAL RESULTS</b>	<b>104</b>
4.1	Metallographic examination	104
4.1.1	P91 samples	104
4.1.2	P92 samples	114
4.2	Hardness measurement	121
4.3	Precipitate investigation using TEM	124
4.3.1	P91 samples	124
4.3.2	P92 samples	131
4.4	Creep rupture testing	134

4.4.1	P91 samples	134
4.4.2	P92 samples	142
4.4.3	Fracture characteristics of creep specimens	146
4.4.3.1	P91 samples	146
4.4.3.2	P92 samples	158
4.5	Summary	166
<b>5.</b>	<b>DISCUSSIONS</b>	167
5.1	Metallographic analysis	167
5.1.1	Comparison of phase transformation and hardness property changes between P91 and P92 alloys	167
5.1.2	Hardness property analysis for P91 and P92 alloys subjected to various peak temperatures	175
5.1.3	Precipitate morphology analysis for P91 and P92 alloys subjected to various peak temperatures	176
5.1.4	Relationship to phase transformation in weldments and risk of failures	178
5.2	High temperature creep analysis	179
5.3	Economical Impact Analysis	191
5.4	Summary	195
<b>6.</b>	<b>CONCLUSIONS</b>	197
6.1	Overview	197
6.2	Material characterization	197
6.3	Remaining creep life prediction	200
6.4	Enhancement of existing practice	201
6.5	Contribution to the body of knowledge	202
6.6	Benefits and value creation to Tenaga Nasional Berhad	202
6.6.1	The benefit to TNBR	202
6.6.2	The benefit to TNB	203
6.7	Suggestions for further work	203

## LIST OF TABLES

<b>TABLE</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	Typical chemical composition of advanced heat resistant ferritic steels (Ennis et. Al., 2002)	19
2.2	Unit cell parameters (a ) of a MX precipitate in ferritic creep-resistant steels	39
2.3	Summary of basic characteristics of minor phases in 9-12%Cr steels	42
3.1	Chemical composition of P91 and P92 creep resistant steels in weight percent	86
3.2	Peak temperatures selected for P91 and P92 specimens	87
3.3	Sample Identification form P91 and P92 specimens	88
4.1	Hardness data for treated P91 specimens	122
4.2	Hardness data for treated P92 specimens	123
4.3	Creep rupture testing results for P91 specimens at design temperature 600°C	138
4.4	Extrapolated creep rupture results for P91 specimens at operating temperature 550°C	139
4.5	Creep rupture testing results for P92 specimens at design temperature 600°C, as recorded up to 31 March 2014.	144
5.1	Phase transformation and hardness variation of laboratory aged P91 and P92 alloys.	168

## LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	(a) Superheater and reheater tube components; (b)header and piping components	3
1.2	Experimental design flow	10
2.1	Continuous cooling transformation (CCT) diagram of grade T/P 91 steels (Haarmann 2002)	27
2.2	Continuous cooling transformation (CCT) diagram of grade T/P 92 steels (Haarmann 2002)	28
2.3a	Schematic illustration of microstructure of tempered martensite 9-12% Cr creep resistant steel, containing precipitates on the grain interfaces.	31
2.3b	Schematic representation of non-uniform precipitation states in tempered martensite 9-12% Cr steels. (Gocmen et al. 1998)	32
2.3c	A schematic drawing of precipitates in high chromium ferritic steel. (Maruyama et al. 2001)	32
2.4	Isopleths phase diagram of T91/P91 steels (Ayala et al. 1999)	33
2.5	Schematic of crystal structure of Cr <sub>23</sub> C <sub>6</sub> carbide with fcc structure.	35
2.6	Schematic of crystal structure of VC carbide with fcc structure.	37
2.7	Schematic of crystal structure of Fe <sub>2</sub> W carbide with hcp structure	40
2.8	Welding and post weld heat treatment cycle of T/P 91. (Haarmann et al. 2002)	46
2.9	Schematic diagram of weld structures. (Lancaster, 1993)	47
2.10	Schematic diagram of multipass welding. (Agyakwa, 2004)	49
2.11	Schematic representation of a high temperature curve (strain vs. time) at constant stress and temperature. (Evans and Wilshire, 1985)	51

2.12	Effect of temperature and stress on strain vs. time creep behavior (Evans, 1984)	52
2.13	Schematic of Ostward ripening mechanism in which larger particles grow up while small particles dissolving into matrix.	63
2.14	(a) Creep curves, and changes in (b) subgrain width and (c) free dislocation density within subgrain during creep of three chromium ferrite steels at 650°C under 98 MPa. (Sawada et al., 1999)	66
2.15	Effect of thermal exposure on hardness as a function of HJP or (LMP) (Agyakwa et al., 2003)	68
2.16a	Isothermal creep rupture curve for Gr. 91 base metal. (Fujimitsu Masuyama et al., 2007)	72
2.16b	Isothermal creep rupture curve for Gr. 91 weldment. (Fujimitsu Masuyama et al., 2007)	72
2.17a	Isothermal creep rupture curve for Gr. 92 base metal (Fujimitsu Masuyama et al., 2007)	72
2.17b	Isothermal creep rupture curve for Gr. 92 weldment. (Fujimitsu Masuyama et al., 2007)	72
2.18	Profile and optical microstructures of the Type IV fractured welded joint specimen. (Watanabe et al., 2006)	74
2.19	Hardness variations in the base metal (BM), heat-affected zone (HAZ) and weld metal (WM) (Watanabe et al., 2006)	74
2.20	Microstructure across weld interface of 2.25Cr-1Mo steel base metal and 9Cr-1Mo steel weld metal of dissimilar joint in various conditions: (a) as welded; (b)PWHT; (c) creep tested (130MPa, 823K) (Laha et al., 2001)	79
2.21	Weld metal failure and inter-bead micro-cracking and cavitation in carbon-depleted regions at the bead boundaries. (Alstom HCM 12A casting weld, P92 weld metal, 625°C, 105 MPa). (Allen et al., 2005)	81
3.1	(a) P91 pipe component; (b) P92 header pipe component.	85
3.2	Test samples of P91 alloys	85
3.3	Test samples of P92 alloys	85
3.4	Schematic diagram of the setup of laboratory furnace and temperature monitoring devices.	89
3.5	Furnaces set up with thermocouples wires and data logger.	89
3.6	Experimental heat treatment curves for P91 and P92 alloys	90

3.7	Continuous cooling transformation diagram for T/P 91 steel	91
3.8	Continuous cooling transformation diagram for T/P 92 steel	91
3.9	Mounted specimens for P91 & P92 alloys	93
3.10	Optical microscope	93
3.11	FE scanning electron microscope	95
3.12	Micro Vicker Hardness Tester	95
3.13	(a) Transmission electron microscope (TEM); (b) Thin film samples for TEM; (c) TEM image from thin film	97
3.14	Schematic of the position and direction of creep specimens taken from P91 and P92 alloys	98
3.15	Schematic drawing of creep specimen.	100
3.16	Creep rupture testing machine	101
3.17(a)	Cylinder type dumb bell shape creep specimens	102
3.17(b)	Close-up view of the cylinder type dumb bell shape creep specimens	102
4.1	As received / as-tempered P91 microstructure. (a) optical micrograph; (b) SEM micrograph.	105
4.2	Transformed P91 microstructure at room temperature after holding 2 hours at 760°C. (a) optical micrograph; (b) SEM micrograph.	105
4.3	Transformed P91 microstructure at room temperature after holding 2 hours at 800°C. (a) optical micrograph; (b) SEM micrograph.	105
4.4	EDX results showing the composition of precipitates in P91 as received specimen.	106
4.5	Transformed P91 microstructure at room temperature after holding 2 hours at 850°C. (a) optical micrograph; (b) SEM micrograph.	107
4.6	Transformed P91 microstructure at room temperature after holding 2 hours at 900°C. (a) optical micrograph; (b) SEM micrograph.	108
4.7	Quenched microstructure after holding 2 hours at 850°C, showing the presence of untempered fresh martensite (dark constituents) and ferrite (light constituents) with an average hardness of 403 HV.	109
4.8	Quenched microstructure at room temperature after holding 2	109



hours at 900°C, showing an almost full transformation of untempered martensite with an average hardness of 489 HV.

4.9	Transformed P91 microstructure at room temperature after holding 2 hours at 950°C. (a) optical micrograph; (b) SEM micrograph.	110
4.10	Quenched P91 microstructure at room temperature after holding 2 hours at 950°C, showing a full transformation to untempered martensite with an average hardness of 496 HV.	111
4.11	Transformed P91 microstructure at room temperature after holding 2 hours at 1000°C. (a) optical micrograph; (b) SEM micrograph, the dark patches are artifacts.	112
4.12	EBSD IPF images of the treated P91 specimens	113
4.13	As received / as-tempered P92 microstructure. (a) optical micrograph; (b) SEM micrograph.	114
4.14	Transformed P92 microstructure at room temperature after holding 2 hours at 760°C. (a) optical micrograph; (b) SEM micrograph.	115
4.15	Transformed P92 microstructure at room temperature after holding 2 hours at 800°C. (a) optical micrograph; (b) SEM micrograph.	116
4.16	Transformed P92 microstructure at room temperature after holding 2 hours at 850°C. (a) optical micrograph; (b) SEM micrograph.	117
4.17	Transformed P92 microstructure at room temperature after holding 2 hours at 900°C. (a) optical micrograph; (b) SEM micrograph.	118
4.18	Transformed P92 microstructure at room temperature after holding 2 hours at 950°C. (a) optical micrograph; (b) SEM micrograph.	119
4.19	Transformed P92 microstructure at room temperature after holding 2 hours at 1000°C. (a) optical micrograph; (b) SEM micrograph.	119
4.20	EBSD IPF images of the treated P92 specimens	120
4.21	Hardness data for heat-treated P91 and P92 samples	123
4.22	Chemical composition of main precipitates in Gr. 91 and Gr. 92 steels. (a)MX, and (b) M <sub>23</sub> C <sub>6</sub>	125
4.23	Sizes of precipitates in P91 steel samples	126
4.24	TEM thin foil images of the P91 specimens subjected to various	127

	peak temperatures.	
4.25	TEM thin foil images of the P91 specimens subjected to a peak temperature of 900°C, showing the evolution of M <sub>3</sub> C phases.	128
4.26	TEM carbon extraction images of the P91 specimens subjected to short term overheating at various peak temperatures.	129
4.27	TEM carbon extraction images of the P91 specimens subjected to cooling from peak temperatures (a) 900°C and (b) 1000°C, showing the evolution of M <sub>3</sub> C phases.	130
4.28	Sizes of precipitates in P92 steel samples	132
4.29	TEM carbon extraction images of the P92 specimens	133
4.30	Creep rupture curves for new and heat-treated P91 specimens at 600°C.	140
4.31	Extrapolated creep rupture curves for new and heat-treated P91 specimens at 550°C.	141
4.32	Creep rupture curves for new and heat-treated P92 specimens at 600°C.	145
4.33	P 91 creep rupture specimen heat-treated at 850°C, tested at 600°C and 100 MPa.	148
4.34	P 91 creep rupture specimen heat-treated at 900°C, tested at 600°C and 130 MPa.	148
4.35	P 91 creep rupture specimen heat-treated at 900°C, tested at 600°C and 160 MPa.	148
4.36	P 91 creep rupture specimen heat-treated at 950°C, tested at 600°C and 160 MPa.	148
4.37	Microstructure images of P 91 creep rupture specimen (part I as shown in Figure 4.34), heat-treated at 900°C, tested at 600°C and 130 MPa.	149
4.38	Microstructure images of P 91 creep rupture specimen (part II, as shown in Figure 4.34) heat-treated at 900°C, tested at 600°C and 130 MPa.	150
4.39	Microstructure images of P 91 creep rupture specimen (part I as shown in Figure 4.35), heat-treated at 900°C, tested at 600°C and 160 MPa.	151
4.40	Microstructure images of P 91 creep rupture specimen (part II, as shown in Figure 4.35) heat-treated at 900°C, tested at 600°C and 160 MPa.	152

4.41	Microstructure images of P 91 creep rupture specimen (part I as shown in Figure 4.36), heat-treated at 950°C, tested at 600°C and 160 MPa.	153
4.42	Microstructure images of P 91 creep rupture specimen (part II, as shown in Figure 4.36) heat-treated at 950°C, tested at 600°C and 160 MPa.	154
4.43	Microstructure images of P 91 creep rupture specimen heat-treated at 1000°C, tested at 600°C and 95 MPa.	155
4.44	Macrostructure & microstructure images of P91 creep rupture specimen heat-treated at 850°C, tested at 600°C and 130 MPa.	156
4.45	Macrostructure & microstructure images of P91 creep rupture specimen heat-treated at 1000°C, tested at 600°C and 90 MPa.	157
4.46	P92 creep rupture specimen heat-treated at 850°C, tested to rupture at 600°C and 130 MPa.	159
4.47	P92 creep rupture specimen heat-treated at 900°C, tested to rupture at 600°C and 130 MPa.	159
4.48	P92 creep rupture specimen heat-treated at 950°C, tested to rupture at 600°C and 100 MPa.	159
4.49	P92 creep rupture specimen heat-treated at 950°C, tested to rupture at 600°C and 130 MPa.	160
4.50	P92 creep rupture specimen heat-treated at 1000°C, tested to rupture at 600°C and 100 MPa.	160
4.51	P92 creep rupture specimen heat-treated at 1000°C, tested to rupture at 600°C and 130 MPa.	160
4.52	Macrostructure & microstructure images of P92 creep rupture specimen heated to 850°C, tested to rupture at 600°C and 100 MPa.	161
4.53	Macrostructure & microstructure images of P92 creep rupture specimen heated to 850°C, tested to rupture at 600°C and 130 MPa.	162
4.54	Macrostructure & microstructure images of P92 creep rupture specimen heated to 900°C, tested to rupture at 600°C and 100 MPa.	163
4.55	Macrostructure & microstructure images of P92 creep rupture specimen heated to 950°C, tested to rupture at 600°C and 130 MPa.	164
4.56	Macrostructure & microstructure images of P92 creep rupture specimen heated to 1000°C, tested to rupture at 600°C and 130	165

	MPa.	
5.1	Continuous cooling transformation diagram for T/P 91 steel.	170
5.2	Continuous cooling transformation diagram for T/P 92 steel.	174
5.3	Demonstration of application of creep rupture curves developed for new and laboratory-aged P91 specimens tested at 600°C.	185
5.4	Demonstration of application of developed creep rupture curves for new and laboratory-aged P92 specimens tested at 600°C.	187
5.5	Demonstration of application of extrapolated creep rupture curves for new and laboratory-aged P91 specimens at 550°C.	190
5.6	Indication of creep rupture time for laboratory-aged tubes with hard microstructure, operated at 600°C and 90 MPa.	193

## LIST OF ABBREVIATIONS

APFIM	Atom Probe Field Ion Microscopy
ASM	American Society for Metals
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BCC	Body Centered Cubic
BM	Base Metal
BSE	Back-Scattered Electron
CCT	Continuous Cooling Transformation
CGHAZ	Coarse Grain Heat Affected Zone
DOSH	Department of Occupational Safety and Health
EBSD	Electron Back-Scattered Diffraction
ECCC	European Creep Collaborative Committee
EDX	Energy Dispersive X-Ray
FCC	Face-Centered Cubic
FE-SEM	Field Emission Scanning Electron Microscope
Fe <sub>2</sub> W	Laves Phase
FGHAZ	Fine Grain Heat Affected Zone
Gr.	Grade
HAZ	Heat Affected Zone
HV	Hardness Vickers
ICHAZ	Intercritical Heat Affected Zone
IGCAR	Indira Gandhi Centre for Atomic Research

IPP	Independent Power Producer
KEPRI	Korea Electric Power Research Institute
LMP	Larson Miller Parameter
Max.	Maximum
Min.	Minimum
MnS	Mangeneses Sulphide
MPa	Mega Pascal
MW	Megawatts
NbC	Niobium Carbide
NbN	Niobium Nitrate
NIMS	National Institute for Material Sciences
OM	Optical Microscope
ORNL	Oak Ridge National Laboratory
PAGB	Prior Austenite Grain Boundaries
PM	Parent Metal
PPTs	Precipitates
PWHT	Post Weld Heat Treatment
QATS	Quality Assurance and Testing Services
SC	Supercritical
SE	Secondary Electron
SJSAS	Stesen Janakuasa Sultan Azlan Shah.
SJTJ	Stesen Janakuasa Tuanku Jaafar.
TEM	Transmission Electron Microscope
TiC	Titanium Carbide
TiN	Titanium Nitrate
TNB	Tenaga Nasional Berhad
TNBJ	TNB Janamanjung
TNBR	TNB Research Sdn. Bhd.
USA	United States of America

USC	Ultra-Supercritical
VC	Vanadium Carbide
VN	Vanadium Nitrate
V & M	Vallourec & Mannesmann
WM	Weld Metal

## LIST OF SYMBOLS

A	-	A constant for Power Law
$A_{c1}$	-	Lower Critical Transformation Temperature
$A_{c3}$	-	Upper Critical Transformation Temperature
a	-	Crystal lattice of unit cell
$\alpha$ -ferrite	-	Alpha Ferrite
$\alpha'$	-	Martensite
b	-	Burgers vector length
$CO_2$	-	Carbon Dioxide
d	-	Particle mean size
$d_0$	-	Initial particle size
$\delta$ -ferrite	-	Delta ferrite
$\epsilon$	-	Creep strain
$\epsilon_F$	-	Strain to failure
$\dot{\epsilon}$	-	Creep strain
$\dot{\epsilon}_s$	-	Steady state creep rate
G	-	Shear modulus
g	-	Gram
$\gamma$ -austenite	-	Gamma Austenite
h	-	Hour
K	-	Dimensional constant
k	-	Boltzmann's constant
k	-	Particle growth rate