



Faculty of Engineering



Cairo University

**ROTATIONAL DRIVES AND SERVICE LIFE ANALYSIS
AND ENHANCEMENT OF MOULDS OF HORIZONTAL
CENTRIFUGAL CASTING MACHINES**

By

MOHAMMED AHMED ALI SHEHATA

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

in

Mechanical Design and Production Engineering

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY
GIZA, EGYPT**

2019

**ROTATIONAL DRIVES AND SERVICE LIFE ANALYSIS
AND ENHANCEMENT OF MOULDS OF HORIZONTAL
CENTRIFUGAL CASTING MACHINES**

**By
MOHAMMED AHMED ALI SHEHATA**

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

**in
Mechanical Design and Production Engineering**

Under the supervision of

Prof. Dr. Saad Kassem

Prof. Dr. Ahmed Bahgat

.....

.....

Mechanical Design and Production
Department

Power Electrical Machines
Department

Faculty of Engineering, Cairo University

Dr. Mohamed Elgamil

.....

Assistant Professor
Mechanical Design and Production Department.

Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2019

**ROTATIONAL DRIVES AND SERVICE LIFE ANALYSIS
AND ENHANCEMENT OF MOULDS OF HORIZONTAL
CENTRIFUGAL CASTING MACHINES**

**By
MOHAMMED AHMED ALI SHEHATA**

A Thesis Submitted to the
Faculty of Engineering at Cairo University
In Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

in

Mechanical Design and Production Engineering

**Approved by the
Examining Committee**

Prof. Dr. Saad Kassem (Thesis Main Advisor)

Faculty of Engineering at Cairo University

Prof. Dr. Ahmed Bahgat (Advisor)

Faculty of Engineering at Cairo University

Prof. Dr. Layla Byoumi (Internal Examiner)

Faculty of Engineering at Cairo University

Prof. Dr. Mervet Badr (External Examiner)

National Research Centre

FACULTY OF ENGINEERING, CAIRO UNIVERSITY

GIZA, EGYPT

2019

Engineer's Name: Mohamed Ahmed Ali Shehata

Date of Birth: 28/7/1976

Nationality: Egyptian

E-mail: shehatamech@gmail.com

Phone: 01008890849

Address: Bortos – Oseem – Giza

Registration Date: 1 / 10 / 2010



Awarding Date:/...../ 2019

Degree: Doctor of Philosophy

Department: Mechanical Design and Production Engineering

Supervisors:

Prof. Dr. Saad Kassem

Prof. Dr. Ahmed Bahgat

Dr. Mohamed A. Elgamil

Examiners:

Prof. Dr. Saad Kassem (Thesis main advisor)

Prof. Dr. Ahmed Bahgat (Advisor)

Prof. Dr. Layla Byoumi (Internal examiner)

Prof.Dr. Mervet Badr (External examiner)
(National Research Centre)

Title of Thesis:

ROTATIONAL DRIVES AND SERVICE LIFE ANALYSIS AND ENHANCEMENT OF
MOULDS OF HORIZONTAL CENTRIFUGAL CASTING MACHINES

Key Words:

Mould, Centrifugal Casting, Service Life, Misalignment, Thermo-mechanical

Summary:

In this research work a centrifugal casting machine driven by a separately excited DC motor and proposed AC motor is investigated. The study has been carried out using two methods of simulation; mathematical modeling and laboratory experiments. The mathematical model has been validated by comparing the simulation results with actual measurements taken with the DC drive. On the other hand, In order to regain the mould expected service life, for improving the operation economic and technical sides, a study of the factors that reduce this life was carried out. The strain measurements were used as indirect indicator for adjusting the mould alignment. The study conclusions were used to develop recommendations and prepare action plans that would improve the mould service life.

Disclaimer

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that i have appropriately acknowledged all sources used and have cited them in the references section.

Name:

Date:

Signature:

ACKNOWLEDGEMENT

A lot of thanks to **GOD** for giving me the power and perseverance to accomplish this work.

I would like to acknowledge with thanks Prof. Dr. Saad Kassem for his contributions and guidance, for his valuable opinions and suggestions throughout the work. His valuable suggestions regarding the thesis layout and his review of the manuscript are much appreciated. I am greatly indebted for his continued, encouragement and patience.

I wish as well to thank Prof. Dr. Ahmed Bahgat for his interest in the work, encouragement, and continuous support. His valuable comments regarding the theoretical and experimental work dedicated to the electric drive and control systems are much appreciated.

I would like also to express my deep gratitude to Dr. Mohamed El Gamil for suggesting the subject of this thesis, his constant guidance and valuable support. He did every possible effort to help and advise me during the course of the research as well as during drafting the thesis. His continuous support and valuable comments are much appreciated.

Also I would like to thank Dr. Bassam Abd EL Latief, department of Mechanical Design and Production for his assistance during the development of the mathematical model and field measurements of mechanical vibrations.

I very much value the support of the management of El-Nasr Castings Company to encourage this research work dedicated to solve two actual-plant problems. Gratitude is also for Eng. M. Naguib and Eng. A. Madian of El-Nasr Castings Company for their co-operation and help.

Finally I deeply thank my family and my wife for the encouragement and patience they showed throughout my Ph.D. study especially throughout the last year during which the thesis was drafted.

TABLE OF CONTENTS

DISCLAIMER	I
ACKNOWLEDGEMENTS	II
TABLE OF CONTENTS	III
LIST OF TABLES	VI
LIST OF FIGURES	VII
LIST OF SYMBOLES	XI
ABSTRACT	XIV
CHAPTER 1: BACKGROUND	1
1.1 Introduction	1
1.2 Centrifugal Casting Principles and Advantages	1
1.3 Components of a Casting Line	2
1.3.1 Pouring Equipment	4
1.3.2. Machine Housing and Components.....	4
1.3.3 Core Setting Equipment.....	6
1.3.4 Cooling Water System.....	6
1.3.5 Pipe Drawing Carriage.....	6
1.4 Description of the Investigated Centrifugal Casting Machine.....	6
CHAPTER 2: LITERATURE SURVEY AND PROBLEM STATEMENT	9
2.1 Literature Survey	9
2.1.1 Electrical Drives Survey.....	9
2.1.2 Mechanical System Survey.....	10
2.1.3 Centrifugal Casting Mould Survey.....	11
2.2 Problem Statement and Scope of Work.....	13
CHAPTER 3: MATHEMATICAL MODEL AND SIMULATION OF MOULDS ROTATION USING DC MOTORS	15
3.1 Mathematical Modeling of the System	15
3.1.1 The DC motor and drive.....	19
3.1.1.1 Four-Quadrant Operation.....	20
3.1.1.2 Motoring Mode.....	21
3.1.1.3 Regenerating Mode.....	21
3.1.1.4 Speed/Torque Relationships of DC Motor.....	22
3.1.2 The System Mathematical Model.....	22
3.1.2.1 System Parts Moments of Inertia Determination	25
3.1.2.2 Practical Determination of the System DampingCoefficient..	27
3.2 System Numerical Simulation.....	29
3.3 System Actual Performance	32
3.4 Comparison between Actual and Theoretical Results.....	35
CHAPTER 4: MATHEMATICAL MODEL AND SIMULATION OF MOULDS ROTATION USING AC MOTORS	37
4.1 Induction Motors Representation and Modeling.....	37
4.1.1 Voltage Equations.....	38
4.1.2 Dynamic Equations of the Two Phase Equivalent Model.....	39
4.1.3 Currents Equations.....	40
4.1.4 State Space Model of the Induction Motor	40
4.1.5 The AC motor and drive.....	41
4.2 System Mathematical Model	43
4.3 System Simulation	44
4.4 Performance Comparison between Systems with DC and AC Motors	

4.5 Costs Considerations	52
4.5.1 Motor Life time Determination.....	52
4.5.2 Capital Cost	53
4.5.3 Life Cycle Cost.....	53
4.5.4 Running Cost Savings.....	54
CHAPTER 5: EXPERIMENTAL COMPARISON BETWEEN DC AND AC DRIVES OF MOULDS	56
5.1 Test Bench Description.....	56
5.1.1 Electrodynamometer	57
5.1.2 DC compound wound motor	57
5.1.3 Three phase squirrel cage induction motor	58
5.1.4 Hand tachometer (Photo-contact Tachometer).....	58
5.1.5 Variable speed drives	59
5.2 Circuit diagrams for the DC compound wound motor	59
5.3 Experimental work.....	60
5.3.1 Test rig set up for DC motor.....	60
5.3.2 Experimental results for the DC motor.....	61
5.4 Circuit diagrams for the squirrel cage induction motor.....	61
5.4.1 Test Rig Set up for AC motor	62
5.4.2 Experimental results for the AC motor.....	64
CHAPTER 6: THEORETICAL STUDY FOR THE FACTORS AFFECTING MOULDS SERVICE LIFE.....	65
6.1 Mould Material.....	65
6.2 Mould's Stresses and Strains	69
6.2.1 Loading Stress.....	70
6.2.1.1 Stresses and Strains due to Mould Weight.....	70
6.2.1.2 Deflection due to bending moment by use of singularity functions.....	73
6.2.1.3 Mould Model Deflection Equations	73
6.2.2 Stresses due to Mould Weight and Misalignments.....	76
6.3 Failure Theories.....	79
6.3.1 Static Loading Analysis.....	79
6.3.2 Mould Dynamic Loading Analysis	80
6.4 Stress Analysis of Mould Subject to the Thermo Mechanical Loads.....	86
6.4.1 Analysis for Mechanical Loading due to Rotation.....	87
6.4.2 Yield Rotational Speed.....	88
6.5 Stresses in the Mould due to Rotation of Cast Metal Pipe.....	89
6.6 Combined Rotational, Thermal and Contact Pressure Stresses in Mould.....	92
6.7 Thermal-Shock and Thermal-Fatigue.....	94
6.7.1 Thermal Strains and Associated Stresses.....	94
6.8 Fatigue life assessment.....	99
CHAPTER 7: EXPERIMENTAL STUDY AND ADJUSTEMENT OF PARAMETERS AFFECTING MOULDS SERVICE LIFE...	105
7.1 Investigation of a Scraped Mould Sample	105
7.1.1 Investigations of Mould with Short Service Life	105
7.1.2 Investigations of Mould with Nominal Service Life.....	110
7.2 Investigations of Mould Misalignment.....	111
7.2.1 Field Strain Measurements	111
7.2.1.1 Adjustment Steps and Calibration.....	111

7.2.2 Field Vibration Measurements.....	111
7.3 Moulds and Pipes Temperatures.....	113
7.3.1 Effect of Water Flow Rate and Pouring Temperature.....	113
7.3.2 Effect of Coating, Mould Rotational Speed and Mould Thicknes	
7.3.3 Effect of Peening on Mould Surface Strengthening	120
CHAPTER 8: IMPLEMENTATION OF RECOMMENDATIONS FOR	
IMPROVING MOULD SERVICE LIFE AND RESULTS...	121
8.1 Implementation Procedures.....	121
8.1.1 Mould Preparation.....	121
8.1.2 Centrifugal Casting Machine Preparation.....	125
8.1.3 Mould Maintenance.....	125
8.2 Implementation Results	126
8.3 Cost Savings	127
8.3.1 Moulds Costs	127
CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE	
WORK	129
REFERENCES.....	130
APPENDIX.....	133

LIST OF TABLES

Table 1.1: Centrifugal casting machine list of parts.....	7
Table 3.1: V- belt Specification.....	17
Table 3.2: Technical data of DC motor 1HQ5-312-5GE40-6JU3-Z	29
Table 3.3: System parameters used for numerical simulation	29
Table 4.1: System parameters of AC motor	45
Table 4.2: DC and AC motor estimated life time.....	53
Table 4.3: DC and AC drive costs.....	53
Table 4.4: DC and AC drive life cycle costs.....	54
Table 5.1: Simulation results for the DC motor	61
Table 5.2: Simulation results for the AC motor.....	64
Table 6.1: Pipe mould chemical composition	65
Table 6.2: Mould material properties	66
Table 7.1: Chemical analysis of failed mould	106
Table 7.2: Tensile test, impact test and hardness measurements of failed mould.....	109
Table 7.3: Chemical composition of mould scraped after its normal service lifetime.....	110
Table 7.4: A comparison of peening parameters for mould size DN1000.....	120
Table 8.1: Average actual productions of pipes size DN1000 per year.....	121
Table 8.2: Peening working speeds for mould size DN1000	122
Table 8.3: Average number of pipes per mould during 2017 and 2018.....	126
Table 8.4: Actual productions of pipes using the moulds size DN1000.....	127
Table 8.5: Mould costs for size DN1000.....	128

LIST OF FIGURES

Figure 1.1: 3-D Isometric of a centrifugal casting system	3
Figure 1.2: Main construction of a centrifugal casting machine	5
Figure 1.3: Mould of a centrifugal casting machines DN1000	6
Figure 1.4: A fragmentary sectional view, in elevation, diagrammatically of centrifugal casting machine.....	6
Figure 1.5: Sectional view taken along line 2-2 of Fig.1.4	7
Figure 3.1: The structure of centrifugal casting machine with belt drive.....	16
Figure 3.2: Schematic representation of the electromechanical drive system.....	17
Figure 3.3: V- belt cross section	17
Figure 3.4: Belt mass-spring-damper system	18
Figure 3.5: Experimentally recorded damped acceleration of the belt free vibration....	19
Figure 3.6: Schematic diagram of controlled-speed drive.....	20
Figure 3.7: Four quadrants of the torque–speed plane.....	21
Figure 3.8: Schematic diagram of motoring mode.....	21
Figure 3.9: Schematic diagram of regenerating mode.....	22
Figure 3.10: Torque and power relations below and beyond base speed.....	22
Figure 3.11: Separately excited DC motor circuit.....	24
Figure 3.12: (a) Dimensions of driving pulley, (b) driven pulley	26
Figure 3.13: The mould dimensions for DN1000.....	26
Figure 3.14: Dimensions of ductile cast iron pipes for DN1000	26
Figure 3.15: Casting of ductile cast iron pipe for DN1000.....	27
Figure 3.16: Practical data of the angular speed as a function of time	28
Figure 3.17: Input motor armature voltage as a function of time	30
Figure 3.18: Motor rotational speed as a function of time	30
Figure 3.19: Mould rotational speed as a function of time	31
Figure 3.20: Motor armature current as a function of time	31
Figure 3.21: Electromagnetic torque as a function of time	31
Figure 3.22: Motor input power as a function of time	32
Figure 3.23: Motor output power as a function of time	32
Figure 3.24: Actual recorded data for (a) voltage (b) current (c) rotation speed	33
Figure 3.25: Actual armature voltages as function of time for pipe DN1000.....	34
Figure 3.26: Actual motor revolution speed as function of time	34
Figure 3.27: Actual armature currents as function of time for pipe DN1000.....	34
Figure 3.28: Actual input power as a function of time for pipe DN1000.....	35
Figure 3.29: Actual and theoretical motor speeds as a function of time for DN1000...35	
Figure 3.30: Actual and theoretical motor currents as a function of time for DN1000..36	
Figure 3.31: Actual and theoretical input power as a function of time for DN1000....36	
Figure 4.1: Three phase, Wye connected AC induction motor	38
Figure 4.2: α - β reference frame equivalent of a 3 phase induction motor	39
Figure 4.3: General arrangement of variable-frequency induction motor drive.....	42
Figure 4.4: General configuration of inverter.....	42
Figure 4.5: Voltage and frequency relations below and beyond base speed.....	43
Figure 4.6: Supply frequency as a function of time	45
Figure 4.7: Stator voltages in stationary reference frame ($V_{\alpha s}$ and $V_{\beta s}$).....	46
Figure 4.8: Stator phase voltages V_a , V_b and V_c respectively	46
Figure 4.9: Stator currents in two phase (a) $i_{\alpha s}$ and (b) $i_{\beta s}$ as a function of time.....	46
Figure 4.10: Stator currents in three phase (a) i_a , (b) i_b and (c) i_c as a function of time.47	
Figure 4.11: Motor rotational speed as a function of time	48

Figure 4.12: Mould rotational speed as a function of time	48
Figure 4.13: Electromagnetic torque as a function of time.....	49
Figure 4.14: Stator real power as a function of time.....	49
Figure 4.15: Motor input power as a function of time.....	49
Figure 4.16: Motor output power as a function of time.....	50
Figure 4.17: Comparison between motor speed as a function of time for DC and AC motor	50
Figure 4.18: Comparison between mould speed as a function of time for DC and AC motor	51
Figure 4.19: Comparison between input power as a function of time for DC and AC motor	51
Figure 4.20: Average expected life versus winding temperature.....	52
Figure 4.21: Motor current versus winding temperature.....	52
Figure 5.1: The lab-volt electromechanical system (EMS).....	56
Figure 5.2: Electrodynamometer	57
Figure 5.3: (a) DC compound motor (b) Equivalent circuit of a dc compound wound	57
Figure 5.4: Squirrel cage induction motor.....	58
Figure 5.5: Hand tachometer	58
Figure 5.6: Variable speed drives, Altivar 32.....	59
Figure 5.7: Circuit diagram for DC compound wound motor.....	59
Figure 5.8: Test rig components for DC compound wound motor	60
Figure 5.9: Circuit diagram for the three phase squirrel cage induction motor.....	62
Figure 5.10: Test rig components for the three phase squirrel cage induction motor	63
Figure 6.1: Dimensions of mould	67
Figure 6.2: Mould continuous time-temperature-transformation diagrams (a) 21CrMo10 (b) 34CrMo4	68
Figure 6.3: Hardening and tempering diagram (a) 21CrMo10 (b) 34CrMo.....	68
Figure 6.4: Schematic drawing of the mould supporting	70
Figure 6.5: Force body diagram of mould model.....	71
Figure 6.6: Free body diagram of the mould model.....	72
Figure 6.7: Variations of the shear force along the mould due to its weight.....	74
Figure 6.8: Variations of the bending moment along the mould due to its weight.....	75
Figure 6.9: Variations of the axial stress along the mould due to its weight.....	75
Figure 6.10: Variations of the axial strain along the mould due to its weight.....	76
Figure 6.11: Schematic diagram for mould misalignment.....	76
Figure 6.12: Variations of the roller support reaction with mould misalignment.....	77
Figure 6.13: Variations of (a) shear forces, (b) bending moments, (c) axial stresses, (d) axial strains along the mould due to its weight and misalignments.....	78
Figure 6.14: Variations of the equivalent stresses with mould misalignments	80
Figure 6.15: Surface finish factors for steel.....	81
Figure 6.16: Schematic diagram for fatigue stress.....	81
Figure 6.17: Fatigue Strength versus (a) No. of cycles (b) No. of pipes at mould strength $\sigma_{ut} = 400$ mould speed $\omega = 140$ rpm and casting temperature $T = 1310^\circ\text{C}$	82
Figure 6.18: Fluctuating stresses.....	83
Figure 6.19: Variations of the mould misalignments versus (a) No. of cycles (b) No. of pipes at mould strength $\sigma_{ut} = 400$, mould speed $\omega = 140$ rpm and casting temperature $T = 1310^\circ\text{C}$	84

Figure 6.20: Variations of the mould misalignments versus No. of pipes at mould strength $\sigma_{ut}= 400$ MPa and casting temperature $T=1310^{\circ}\text{C}$	85
Figures 6.21: Variations of the mould misalignments versus No. of pipes at mould strength $\sigma_{ut}= 400$ MPa, casting temperature $T=1310^{\circ}\text{C}$ and mould speed $\omega = 140$ rpm.....	85
Figures 6.22: Variations of the mould misalignments versus No. of pipes at mould speed = 140 rpm and casting temperature $T=1310^{\circ}\text{C}$	86
Figure 6.23: Mould thermo-mechanical load distributions.....	86
Figure 6.24: Variations of the radial along the mould thickness subjected to inertia force due to rotating at 140 rpm.....	87
Figure 6.25: Variations of the radial, hoop and axial stresses along the mould thickness subjected to inertia force due to rotating at 140 rpm.....	88
Figure 6.26: Variations of maximum shear stress versus mould speeds.....	89
Figure 6.27: Variations of the radial stress of mould subjected to inertia force due to rotating of cast pipe at 140 rpm.....	90
Figure 6.28: Variations of the radial along the mould wall thickness.....	91
Figure 6.29: Variations of the radial, hoop and axial stress along the mould thickness subjected to inertia force due to rotating of cast pipe, $\omega =140$ rpm and internal pressure P_c	91
Figure 6.30: Variations of the radial stress along the mould wall thickness.....	93
Figure 6.31: Variations of the radial stress, hoop stress and axial stress along the mould thickness subjected to inertia force due to rotating of cast pipe, $\omega =140$ rpm rad/s and temperature gradient (650°C - 100°C).....	93
Figure 6.32: Variations of equivalent von misses stress versus mould thickness.....	94
Figure 6.33: Temperature variation at different points of the centrifugal casting mould wall as a function of time from the start of casting at casting temperature 1350°C	96
Figure 6.34: Stresses variation at different points of the centrifugal casting mould wall as a function of time from the start of casting.....	97
Figure 6.35: Graphic illustration of (a) temperature (b) thermal stress (c) thermal strain profile in a pipe mould wall produced during pipe casting cycles.....	98
Figure 6.36: The strain range versus (a) No. of cycles (b) No. of pipes.....	100
Figure 6.37: Casting temperatures versus number of pipes.....	101
Figure 6.38: Variations of the strain range versus number of pipes at ultimate tensile strength $\sigma_{ut}= 400$ MPa, ductility $D=0.17$, Young's modulus $E=170$ GPa, casting temperature $T=1310^{\circ}\text{C}$, pipe production rate 16 pipes/hr and casting time $R=3.75$ min. per pipe.....	101
Figures 6.39: Variations of the strain range versus No. of pipes at ultimate tensile strength $\sigma_{ut}= 400$ MPa, ductility $D=0.17$, Young's modulus $E=170$ GPa, mould speed = 140 rpm, pipe production rate 16 pipes/hr and casting time $R=3.75$ min. per pipe.....	102
Figures 6.40: Variations of the strain range versus No. of pipes at ductility $D=0.17$, Young's modulus $E=170$ GPa, mould speed = 140 rpm, pipe production rate 16 pipes/hr, casting temperature $T=1310^{\circ}\text{C}$, and casting time $R=3.75$ min. per pipe.....	102
Figures 6.41: Variations of the strain range versus No. of pipes at ultimate tensile strength $\sigma_{ut}= 400$ MPa, ductility $D=0.17$, Young's modulus $E=170$ GPa, mould speed = 140 rpm, casting temperature $T=1310^{\circ}\text{C}$, and casting time $R=3.75$ min. per pipe.....	103

Figures 6.42: Variations of the strain range versus No. of pipes at ultimate tensile strength $\sigma_{ut}= 400$ MPa, pipe production rate 16 pipes/hr, Young's modulus $E=170$ GPa, mould speed = 140 rpm, casting temperature $T=13100C$, and casting time $R=3.75$ min. per pipe.....	103
Figures 6.43: Variations of the strain range versus No. of pipes at ultimate tensile strength $\sigma_{ut}= 400$ MPa, ductility $D=0.17$, Young's modulus $E=170$ GPa, mould speed = 140 rpm, pipe production rate 16 pipes/hr and casting temperature $T=13100C$	104
Figure 7.1: (a) Network cracks of the mould inner surface (b) Mould specimen	106
Figure 7.2: Crack tip Image from Scanning Electron Microscope Analysis.....	107
Figure 7.3: Crack tip microstructure (polished and etched crack tip).....	108
Figure 7.4: Internal microstructure of mould metal.....	108
Figure 7.5: Mould mechanical properties as a function in temperature.....	109
Figure 7.6: (a) Mould fixation (b) Roller support.....	112
Figure 7.7: Strain gauge fixation at the inner surface of the mould	113
Figure 7.8: Temperatures of the outlet cooling water flow rates and mould inner surface temperature.....	114
Figure 7.9: Effect of water flow rate on the solidification time at different pouring temperatures and casting period 27 sec.....	115
Figure 7.10: Effect of pouring temperature on the solidification time at different casting periods and water flow rate $130\text{ m}^3/\text{hr}$	115
Figure 7.11: Schematic diagram of experimental setup for mould specimen.....	116
Figure 7.12: Highest temperature on the inside of the mould as a function of the casting temperature.....	117
Figure 7.13: Effect of surface temperature of mould on structure and notch impact toughness.....	117
Figure 7.14: Effect of the coating powder on the solidification time.....	118
Figure 7.15: Effect of the mould rotational speed on the solidification time.....	118
Figure 7.16: Effect of the coating powder on the peak temperature of mould inner surface.....	119
Figure 7.17: Effect of the mould thickness on the solidification time.....	119
Figure 8.1: Ultrasonic scanning of mould outer surface.....	122
Figure 8.2: Ultrasonic test system.....	123
Figure 8.3: Ultrasonic examination scanning for mould without internal defect.....	124
Figure 8.4: Ultrasonic examination scanning for the mould with internal defect.....	124
Figure 8.5: The mould actual productions of pipes per mould	127