In-process monitoring and characterization of arc welding

Wong, Yoke Rung

2012

Wong, Y. R. (2012). In-process monitoring and characterization of arc welding. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/53621>

<https://doi.org/10.32657/10356/53621>

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IN-PROCESS MONITORING AND CHARACTERIZATION OF ARC WELDING

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

2012

ABSTRACT

Inspection of weld quality is critical because it ensures the integrity of structures. There are many available methods for monitoring and diagnosis of the weld quality. However, most of them are off-line and thus make the quality monitoring and remedial measures difficulty and costly. In this research, a real-time quality monitoring and diagnosis method based on the input electrical impedance of the arc welding is proposed. It is obtained by taking the quotient of input voltage to current which both signals are measured simultaneously at the output terminal of welding machine. Two time record data, real part and imaginary part, or the resistance and reactance of impedance reflect the system property of arc welding which is represented by an equivalent circuit. This equivalent circuit consists of resistor, inductor and capacitor connected in series. Therefore, any abnormal change of arc welding will be reflected by the time variation of these components.

Several major findings were obtained from this research. The mean and standard deviation of resistance and reactance of impedance are affected by the operating parameters such as welding voltage, current, welding speed, free wire length and leading angle of welding torch. Further investigation of impedance also leads to have a more accurate heat input per unit length by including the resistance of impedance. The implementation of Taguchi Method and Macro Testing shows that the proposed method can achieve 95% accuracy of detecting weld defects. Furthermore, the proposed method

ABSTRACT

is also capable to diagnose the weld defect as result of abrupt change of arc length or wrong welding speed.

The capability of proposed method is further extended to provide real-time and in-situ information of metal transfer. The time varying resistance and reactance curves reflect the dynamic change of metal transfer like the formation and detachment of droplet to the weld pool. This in-situ information helps to develop a new classification method of metal transfer which the metal transfer modes are quantified in percent weightage. Furthermore, the study of welding metallurgy indicates that the metal transfer mode shown in percent weightage is correlated with the macro structural change of weld but not the micro structural change of weld.

ACKNOWLEDGEMENT

Firstly, I would like to thank my supervisor, Professor Ling Shih-Fu for his guidance, help and support in my research. Without him, this thesis could not be completed.

Secondly, I also want to thank my colleagues, Mr Pang Xin, Liang Kar Foong, Ivan Tanra, Ju Feng, the technicians and research students in Mechanics of Machines Lab, Center for Mechanics of Micro-systems, Service Workshop A and Material Lab A where they provide me a lot of helps and supports so that I can focus to do my research smoothly.

Lastly, I would like to also thank my families, especially my wife, Xing Xuan, for their continuous and unconditional encouragements and cares.

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NOMENCLATURE

ROMAN SYMBOLS

A	Cross-sectional area, m^2
C	Capacitance, F
d	Distance, m
h	Heat input, J
I	Weld current, A
ℓ	Arc length, m
L	Inductance, H
P	Air pressure, atm
Q	Heat flux, W/m^2
R	Resistance, Ω
t	Time, s
T	Temperature, $^{\circ}C$
v	Welding speed, mm/s
V	Voltage, V
V_L	Induced voltage, V
Z_{in}	Input electrical impedance, Ω
Z_r	Real part or resistance of Z_{in} , Ω
Z_x	Imaginary part or reactance of Z_{in} , Ω

GREEK SYMBOLS

α	Degree of ionization
η	Arc energy transferred efficiency
θ	Leading angle, $^{\circ}$
ω	System frequency, Hz

NOMENCLATURE

ρ	Electrical resistivity, Ω/m
ε	Dielectric constant
γ	Reinforcement angle of weld bead, $^{\circ}$

CHAPTER 1

INTRODUCTION

Fusion welding is a very important manufacturing process in joining material. Due to different requirements of fusion welding, various types of welding processes have been used. These welding processes can produce good weld quality if the operating parameters, materials, welding joints and welding positions are set correctly. Furthermore, the welding mechanism such as metal transfer also plays a major role in fusion welding to ensure the weld quality. In order to determine the weld quality, the destructive and non-destructive quality testing is implemented. These testing are usually conducted off-line because most of the weld defects cannot be detected immediately. Therefore, there is a trade-off between the productivity and weld quality because re-work on those defective welding joints is essential and increases the cost of production. To reduce this trade-off, real-time quality monitoring method is desirable. In this chapter, the background of fusion welding and developing a real-time quality monitoring method, objectives and scope of work are presented. Furthermore, the construction of this thesis is shown at the end of the chapter.

1.1 Background

Fusion welding is commonly used in manufacturing process to join parts together by heat and sometime with pressure. As shown in Fig. 1.1, there are various types of fusion welding which are used for specific requirements. In general, Flux Cored Arc Welding

(FCAW) and Gas Metal Arc Welding (GMAW) are the most commonly used welding processes. They allow faster welding process and better weld quality due to the double protection by the shielding gas and a top layer of slag. This slag layer is formed by the granular core material (flux), which is filled inside the welding wire. As comparing with FCAW and GMAW, Shielded Metal Arc Welding (SMAW) can be performed with relatively inexpensive equipment and filler metal, moderate experienced operator but slow in welding process. Submerged Arc Welding (SAW) is a high-productivity welding process because larger current (above 900A) can be used for higher metal deposition rate. Gas Tungsten Arc Welding (GTAW) or also known as Tungsten Inert Gas (TIG) welding uses non-consumable tungsten electrode, inert gas and separate filler metal. This welding process provides a stable welding arc and requires advanced operating skill, which makes it superior to weld metals like stainless steel, copper alloys and nickel alloys. Others welding processes such as Resistance Spot Welding, Laser Welding and Electron Beam Welding are also important but they are not discussed in this thesis.

Figure 1.1 Types of fusion welding.

Based on the literatures, the operating parameters, materials, welding joints and welding positions can affect the welding mechanism and therefore the weld quality. For the operating parameters, welding voltage, current, free wire length, welding speed, leading angle of welding torch, welding wire diameter, welding wire feed rate and the shielding method are important in order to achieve good weld quality. Basically, the shielding method includes the use of welding wire with coating or flux, external supply gas or both together depending on the requirements of welding process. The coating or flux is usually made of various chemicals and metal powders. On the other hand, the gas is supplied separately for protecting the molten material. Carbon Dioxide (CO₂) and Argon (Ar) gas are commonly found in the FCAW and GMAW. On the other hand, Ar gas and inert gases like Helium (He) are used for GTAW. Other gases like Nitrogen (N₂), Hydrogen (H₂) and Oxygen (O₂) may also be involved. In this case, the flow rate of supplied gas becomes one of the important operating parameters.

In theory, all material is possible to be welded. However, the easiness of welding is depended on the weldability of material. For the metal welding, we focus on the carbon and its alloy steel. Based on the weldability of steel, it can be divided into six groups [1]: Carbon steel, high strength low alloy steel, quenched-and-tempered steel, heat-treatable low alloy steel, Chromium-molybdenum steel and coated steel. The carbon steel can be further divided into mild steel, medium and high carbon steel depending on the content of carbon from low to high percent. For the weldability, mild and medium carbon steel has no difficulty in welding with additional welding procedures such as preheat, postheat and etc. However, the weldability of high carbon steel is poor. Other groups of steel have similar weldability as mild and medium carbon steel but they may require some special welding procedures to maintain good weld quality.

The welding joint design and welding position selection also play a major role in welding. Basically, the edges of two separated metals need to be prepared before welding. Butt, lap, corner and T-joint are the basic types of welding joint designs. More complicated types and variations of welding joint designs can also be found in the welding handbook [2]. Due to the geometrical constraint of structures, it requires the weld to be done in different positions. Four commonly seen welding positions are flat, horizontal, vertical and overhead [3].

According to Lancaster [4], the welding mechanism consists of two parts: Heat flow and mass flow. The heat flow involves the heat input by heat source, heat transfer from the heat source to the welding wire and parent metal and then determines the nature of weld thermal cycle. Therefore, it affects the welding metallurgy. On the other hand, the mass flow refers to the flow of metal from welding wire to weld pool (also known as metal transfer) and the flow of metal in the weld pool (also known as weld pool oscillation). The metal transfer can be used to indicate the metal deposition rate and temperature distribution but the geometry of weld bead is related to the weld pool oscillation. Furthermore, the mass flow may also cause irregularity in heat flow and therefore affect the metallurgical change of weld.

In welding, weld quality is the most critical factor because it has to ensure that the welding joints can satisfy the safety requirements in order to prevent the unpredictable failure of welding joints. Based on the literatures, the defects of welding joints can be divided into two groups [5]: Welding imperfections and metallurgical imperfections. Porosity, Slag inclusion, lack of fusion, undercut, cracks and etc are belonged to the welding imperfections. They are normally caused by improper welding or technological conditions of welding. On the other hand, the metallurgical imperfections consist of the

cracks or micro cracks, voids and segregation of microstructure due the unfavorable micro structural change in the weld bead. Since the weld defects usually degrade the weld quality, it is important to understand the problem of weld quality by studying the definitions, causes and inspections of these weld defects.

There are plenty of quality inspection methods available to determine the weld quality. Basically, it involves two major groups of inspection methods which are destructive and non-destructive testing. The destructive testing really means that workpiece is destroyed by mechanical testing in order to obtain the result of weld quality. The mechanical testing can be tensile test, bend test, impact test, hardness test and metallographic test. AWS, BS, JIS and other international standards [6] provide the guidelines and tables of quality standard for the above tests. In general, the destructive testing is relatively easy to conduct and requires less expensive equipments but the completely destruction of workpiece is expensive and time consuming. Therefore, it is only good for testing new material or new welding process.

The non-destructive testing is more widely used than destructive testing because it can determine the weld quality without destroying workpiece. Ultrasonic Test and Radiography Test can detect most of the defect types. Other methods like Eddy Current Test, Magnetic Particle Test, Liquid Penetration Test and Acoustic Emission Test are also available for specific reasons. However, these testing can only be applied off-line mostly. Re-work on the welded joint has to be done after defect is detected by the test. Therefore, the productivity is “traded off” for good weld quality.

For retaining both high productivity and good quality, real-time quality monitoring method plays a major role in the current state of art technology. The real-time quality

monitoring method refers to a specific technique which is able to provide monitored or diagnosed result of weld quality during the welding process. In welding, voltage and current are the most commonly used monitoring signatures for quality inspection. Wu *et al.* [7] adopted double stages statistical signal processing method to obtain statistical control chart and Di Li *et al.* [8] tried to perform pattern recognition and classification via self-organizing feature map neural network method. Besides the voltage and current, other monitoring signatures like infrared [9], laser vision [10], electromagnetic emission [11] and plasma spectroscopy [12, 13] are also employed and correlated with the weld quality.

Recently, Ling and his team have developed a real-time quality monitoring method based on the input electrical impedance of a system. This input electrical impedance is capable to reflect the behavior of a dynamic system because it is an inherent property of the system. Practically, the applications of this method have been confirmed by performing quality monitoring on RSW [14], ultrasonic welding [15] and wire bonding [16]. Therefore, the same concept can be applied in fusion welding to correlate the input electrical impedance with the weld quality and welding mechanism.

1.2 Research Objectives, Scope of Work and Research Plan

This research work aims to make use of the input electrical impedance for developing a real-time monitoring and diagnosis method. This method is proposed for the purpose of:

- (1) Monitoring the weld quality and providing diagnosed result instantly.
- (2) Revealing the in-situ of welding mechanism such as metal transfer phenomena and metallurgical change of weld.

Fig. 1.2 demonstrates the scope of work and research plan. Basically, the research plan follows Stage 1 to 3. At Stage 1, the operating parameters of welding are evaluated based on one type of material, welding joint and position. The important operating parameters like welding voltage, current, welding speed and etc are literally reviewed to establish the basic knowledge of welding so that their variations can be correlated with the input electrical impedance. The results obtained in Stage 1 are important because it allows the development of real-time monitoring and diagnosis method for the welding imperfections such as lack of fusion, porosity and etc. This task will be completed in Stage 2. Furthermore, the developed method is believed to provide a measuring tool to investigate the relationship between the input electrical impedance and welding mechanism. In Stage 3, we will focus on the in-situ of mass flow like metal transfer and its effects on the metallurgical change of weld. For the heat flow, we are only interested on the investigation of heat input.

Figure 1.2 Scope of work and research plan.

1.3 Organization of Thesis

This Thesis consists of 7 chapters. Chapter 1 generally gives introduction, background, objectives and scope of research work. Chapter 2 reviews the welding mechanism, welding metallurgy, working principle, operating parameters, weld quality and its inspection methods of fusion welding. Chapter 3 presents the relationship between the operating parameters and input electrical impedance. Furthermore, a more accurate heat input per unit length is obtained by employing the resistance of impedance. By using the proposed method, real-time quality monitoring and diagnosis of fusion welding can be achieved and demonstrated in Chapter 4. In order to realize the achievements made in this research, a prototype of real-time monitoring and diagnosis apparatus has been designed and built. Chapter 5 and 6 demonstrate the enhanced capability of proposed method in real-time and in-situ study of welding mechanism by investigating the relationship between the input electrical impedance with the metal transfer phenomena and metallurgical change of weld. Finally, the important findings, conclusions and future research work are drawn in Chapter 7.

CHAPTER 2

FUSION WELDING

In this chapter, the mechanism of fusion welding, welding metallurgy of carbon steel, operating principle of FCAW, welding imperfections and its quality assurance are discussed. Section 2.1 presents four major characteristics of welding mechanism: heat source, heat input per unit length, shielding method and mass flow. Section 2.2 discusses the metallurgical change of weld for carbon steel. Section 2.3 demonstrates the operating principle of FCAW and the effects of various operating parameters on the weld quality. Section 2.4 shows various types and causes of weld defects based on welding imperfections. Section 2.5 emphasizes on the importance of quality assurance for welding, the current state of art technology for quality monitoring methods, and the need for developing a real-time quality monitoring and diagnosis method.

2.1 Fusion Welding Processes

Heat source, heat input per unit length, shielding methods and mass flow are four fundamental characteristics of fusion welding. Each of them can be used to describe the nature of welding process and subsequently help to optimize the operating parameters such as voltage, current, welding speed and etc. In the followings, the heat source, heat input per unit length, shielding methods and mass flow are discussed in detail.

2.1.1 Heat Source

For fusion welding, three types of energy sources are available as shown in Table 2.1 [17]. Fig 2.1 shows the heat source density, energy spread and energy level for different types of energy source. The heat source density, expressed in W/cm^2 , determines how much the heat flux is generated. Based on their nature in heat generation, the heat source density can vary for different types of energy source. For energy spread, it actually refers to the concentration of the thermal energy. As shown in Fig. 2.2, the laser beam has the highest concentration while the oxy-fuel flame (gaseous combustion) has the lowest. Based on different requirements, the proper welding process is selected for the particular welding job.

Table 2.1 Types of energy source.		
1.	Thermo-chemical energy	Gaseous combustion.
2.	Electro-thermal energy	Electric arc (ionization of gas) or electrical resistance (passing current through the parts).
3.	Focused energy	Electron bombardment or laser.

The electric arc, or commonly known as welding arc, is one of the important heat sources due to its high energy level and relatively good thermal concentration. Basically, it is a high current and low voltage discharge in the range of 10 – 2000A and at 10 – 50V. The mechanism of welding arc is complicated because it involves the “evaporated” electrons from cathode being transferred through an ionized gaseous region to the anode. Table 2.2 shows the complexity of the welding arc by dividing it into five parts based on the potential difference (as shown in Fig. 2.3).

Table 2.2 Detail description of welding arc.		
1.	Cathode spot	The tip of electrode emits numbers of electrons by either photo-electric effect or the Schottky effect as a result of dielectric burst.
2.	Cathode drop	A gaseous region near to the cathode spot where a sharp drop of potential occurs.
3.	Arc column	Bright, high temperature, low potential gradient and highly ionized gas.
4.	Anode drop	A gaseous region near to the anode spot where another sharp drop of potential occurs.
5.	Anode spot	The surface of workpiece where the electrons are condensed.

Figure 2.1 Thermal density and spread for different heat source [17].

Figure 2.2 Concentration of thermal energy [17].

Figure 2.3 Potential drop of welding arc.

At the cathode spot and cathode drop, the electrons are emitted and accelerated towards the anode with sufficient potential difference. Due to the impacting, the gas is ionized and more electrons are free from the atoms of gas. The rapid increase of electrons help to carry the current charge and the gas in between the cathode and anode becomes electrically conductive. Subsequently, the welding arc is formed.

The welding arc is electrically neutral and substantially in thermal equilibrium because the numbers of electrons and positive ions in the column are equal. Equation 2.1 [18] shows that the degree of ionization, α , is a function of temperature and pressure. An example of the single ionization of argon gas is shown in Fig. 2.4 to demonstrate the relationship between the degree of ionization, pressure (P) and temperature (T). It clearly implies that the ionization of gas happens at high temperature. Typically, the temperature varies in different parts of the arc: (i) 2500°C at the cathode; (ii) 3500 °C at the anode; (iii) 5000 °C in the welding arc. Therefore, such high temperature provides sufficient thermal energy to melt its adjacent material.

$$\frac{\alpha^2}{1 - \alpha^2} = \frac{P_0}{P} \left(CT^{\frac{5}{2}} e^{-\frac{x}{kT}} \right) \quad (2.1)$$

Figure 2.4 Degree of ionization for single argon under different pressure [18].

The welding arc has direct effect on the weld quality. The requirements of forming a stable arc are:

- (1) High temperature at the cathode to intensify the emission of electrons.
- (2) Sufficient potential difference so that the electrons can accelerate to faster speed, impact and ionize the gas molecules.
- (3) Enough positive ions in the gaseous environment.

In order to achieve a stable arc, the operating parameters such as voltage, current and etc have to be set and controlled carefully. Any disturbance causing these parameters to deviate over a period of time should be avoided. The effects of the important operating parameters on the welding arc are discussed in the next section.

2.1.2 Heat Input per Unit Length

The heat input per unit length is expressed as [18]:

$$\frac{q}{v} = \frac{\eta VI}{v} \quad (2.2)$$

The V and I represent the welding voltage and current, which their multiplication defines the total power input. By including the proportion of arc energy transferred to the material, η and the welding speed, v , it computes the heat being consumed to melt the metal with respect to the unit length of weld bead. Theoretically, the η is usually equal to 1 when we assume that no losses are incurred during the energy conversion. The heat input per unit length is another important parameter in fusion welding because it determines the heating rate, cooling rate, metal deposition rate and weld pool size. Basically, the higher heat input per unit length is able to obtain larger weld pool but lower cooling rate. Larger weld pool always produces larger heat-affected zone which causes the material hardness to reduce and metallurgical defect for welding. However, lower cooling rate can reduce the possibility of hydrogen-induced cracking after solidification.

As mentioned above, the metallurgical defect can be due to the grain size in the heat-affected zone or base metal. The grains in the solidified weld pool grow concurrently with grains in the heat-affected zone. For higher heat input per unit length, the grains undergo a longer thermal cycle and hence longer time stay above the grain-coarsening temperature. The coarser grain size is undesired as it reduces the ductility significantly for ferritic steels.

2.1.3 Shielding Methods

For consumable welding, the molten droplets at the tip of welding wire and weld pool are substantially above the melting temperature. At such high temperature, the oxidation of the molten material with the oxygen and nitrogen are rapid. Common defects like porosity, cracking and embrittlement are usually found in the weld as result of rapid oxidation. Therefore, some forms of shielding to prevent the oxidation are required. This protection can be achieved by using coating, flux, gas or combination of the two and their extension.

For Shielded Metal Arc Welding (SMAW), the coated welding wire is used. The coatings are composed of minerals, organic material, ferro-alloys and iron powder bonded with sodium or potassium silicate. During the welding process, the weld droplets and weld pool are coated with slag. For Submerged Arc Welding (SAW), the flux is granular powder, which is applied on the welding wire and weld pool immediately ahead of the arc. This flux melts around the welding arc and forms the protective shield.

Shield obtained by means of external gas supply is used in Gas Metal Arc (GMAW) and Gas Tungsten Arc (GTAW)). The gas discharges continuously through a nozzle and surrounds the welding wire and weld pool. There are several types of gases used in welding. For non-ferrous metals and Gas Tungsten Arc Welding, the argon or helium gas are used. On the other hand, pure carbon dioxide or its mixture with argon are preferable for Gas Metal Arc Welding because carbon dioxide inhibits cathode spot wander and promotes smooth operation.

For Flux Cored Arc Welding (FCAW), the combination of flux and gas is used. The flux is contained in a metal tube to form the welding wire. Similar to Gas Metal Arc Welding, the shielding gas is dispensed through a nozzle while the wire is fed to the weld pool continuously. Therefore, this shielding method possesses both advantages of using flux and gas.

Incorrect use of shielding gas can cause serious degradation of weld quality (see Fig. 2.5). Weld defects like porosity, blow hole, inclusion and lack of fusion can be attributed to the shielding gas under various welding conditions which are listed in Table 2.3.

Table 2.3 Weld defects due to different conditions of shielding gas.		
1.	Flow Rate	Either inadequate or excessive flow results in porosity and blow hole (as seen in Fig. 2.5(a)).
2.	Torch Angle	A large angle can cause porosity (as seen in Fig. 2.5(b)).
3.	Torch Design & Adjustment	An off center of electrode and incorrect size of contact tube diameter can result in unbalanced flow (as seen in Fig. 2.5(c)).
4.	Nozzle Condition	The nozzle caked with spatter can choke the flow (as seen in Fig. 2.5(d)).
5.	Environment Condition	The sudden change of air current in the region of arc can reduce the effectiveness of gas shielding.

Figure 2.5 Incorrect use of shielding gas.

2.1.4 Mass Flow

Mass flow is one of the important welding mechanisms beside heat flow. For consumable arc welding, it governs two mass flow phenomena: Flow of metal from welding wire to weld pool; Flow of metal in the weld pool. The first one is conveniently known as metal transfer and the second one is weld pool oscillation. In the following, the physics of both mass flows will be discussed in order to understand the in-situ of welding.

2.1.4.1 Metal Transfer

The metal transfer of molten droplet from welding wire to weld pool is always in focus because it is related to the welding arc stability, weld bead appearance and quality. According to Lordacescu *et al.* [19], they reviewed various types of the metal transfer mode classifications which are used to describe the metal transfer phenomenon: natural

vs. controlled, variants vs. variances and mixed vs. combined. Generally, there are three fundamental modes based on the physical phenomena (see Fig. 2.6):

(i) Short-Circuiting Transfer Mode

The welding arc is short and regularly interrupted by a bridge of molten metal between the welding wire and weld pool. As a result, the current is short-circuited. The detachment of “bridge” is governed mainly by surface tension force which acts vertically on the molten metal.

(ii) Globular Transfer Mode

A single molten droplet of metal is formed at the tip of welding wire and detached to the weld pool. Its size is bigger than the diameter of welding wire but the transfer rate of droplet is slower. In this mode, the gravity resultant force is responsible for the detachment of droplet.

(iii) Spray Transfer Mode

The size of droplet is always smaller than the diameter of welding wire. Since the size of droplet is small, the transfer rate of droplet becomes streaming because it is as fast as a real “shower”. The main governing force is the arc pressure resultant which assures the projection of the droplets toward the weld pool.

Figure 2.6 Schematic diagrams of metal transfer phenomena.

Since the metal transfer mode describes and classifies the physical phenomena, two important factors, the size and transfer rate of droplet are suitable for the metal transfer mode classification. However, these factors are difficult to measure due to the harsh environment when performing welding job. In practice, the metal transfer is commonly classified based on the welding voltage, current or wire feed rate because they can be directly correlated with the metal transfer (see Fig. 2.7). Another advantage of this classification is the metal transfer can be related to the operating parameters so that it helps the design of welding job.

The study of metal transfer shows that the formation and detachment of droplet is affected by the dynamic coupling between the welding wire, droplet and welding arc. This dynamic coupling includes the interaction of acting forces such as inertia, gravity, surface tension, magnetic force, viscous drag force and arc pressure. Eventually, the resultant forces decide the size and transfer rate of droplet.

Figure 2.7 Metal transfer mode classification (U_o is voltage and I_w is current) [19].

Two simplified theoretical models have been used to describe the effects of the acting forces. Static Force Balance Theory (SFBT) is developed to determine the size of droplet from the balance of forces using surface tension as an attaching force and gravity, magnetic force as detaching forces. However, this model is only suitable for the Short-circuiting or globular transfer mode at low current welding because the radial component of the magnetic force has been neglected. For high current welding corresponding to the spray transfer mode, Pinch Instability Theory (PIT) is used to obtain the size of droplet. It considers the instability in a column of liquid metal due to the influence of magnetic pressure within the liquid metal. In the region of transition from globular to spray transfer mode, both theories have been failed to obtain the correct size of droplet.

More complicated models have been proposed in order to improve the feasibility and accuracy of the numerical models. Haidar [20] proposed a dynamic two-dimensional arc model to investigate the effects of the various forces acting on the droplet. He found that the gravity force plays an important role for globular transfer mode but the radial component of the magnetic force is the major detaching force in spray transfer mode.

Nemchinsky [21] adopted a liquid type pendent droplet to analyze the effects of surface tension and magnetic force acting on the molten tip of welding wire. On the other hand, the detachment of droplet at the tip of welding wire was modeled by a dynamic force balance model to predict the resonant frequency and detaching size of droplet [22]. All the numerical models work reasonably well in their respective range and they provide a good reason to study the physical phenomena of metal transfer.

2.1.4.2 Weld Pool Oscillation

The final shape of weld bead is highly depended on the molten motion in the weld pool which affects the weld quality after solidification. Sindo [3] has summarized the driving forces for the weld pool oscillation and shown in Fig. 2.8. Buoyancy and magnetic force help to move the liquid metal from the top to the bottom of weld pool and therefore create deep weld penetration. However, the surface tension force induced by surface tension gradient and arc shear stress induced by plasma jet tend to move the liquid metal outward along the pool surface only.

Buoyancy force becomes an important force to transfer the hotter liquid metal to the bottom of weld pool. Due to the temperature difference between the top and bottom of weld pool, the hotter liquid metal from the welding wire sinks to the bottom of weld pool at lower temperature and creates the oscillation. Magnetic force is another important force to drive the hotter liquid metal to the bottom of weld pool. Basically, this magnetic force is induced by the welding current which is proportional to the welding current squared. Similar to the effect of buoyancy force, it pushes the liquid metal inward and downward along the pool axis. Therefore, both forces have significant influence on the weld penetration.

Figure 2.8 Driving forces for the weld pool oscillation.

The interest to study the factors affecting the magnetic force is high due to its complicated nature of formation. Nemchinsky [22], Kumar & Debroy [23] have proposed numerical models to calculate the distribution of magnetic force in a weld pool. They confirmed that the arc movement and current distribution affect the magnetic force acting on the weld pool. On the other hand, Traidia & Roger [24] developed a finite element model to solve the induced magnetic field by including the heat transfer and fluid flow pattern of weld pool. As a result, the weld penetration is predicted after solidification.

In the absence of a surface-active agent, the surface tension of liquid metal decreases with increasing temperature. Therefore, the hotter liquid metal with lower surface tension at the center of weld pool is pulled outward by the cooler liquid metal with higher surface

tension at the edge of weld pool. On the other hand, the shear stress along the weld pool surface is induced by the motion of plasma at high speed. It causes the liquid metal to flow from the center to the edge of weld pool surface. In this case, both forces have minor effect on the weld penetration but they affect more on the width of weld bead and then the reinforcement angle of weld bead.

2.2 Welding Metallurgy

The metallurgical change of weld mainly takes place at the fusion zone (weld metal) and heat-affected zone (HAZ). Fig. 2.9 shows that the grain structure growth at the weld metal depends on two factors: composition (solute content) and solidification parameter. Basically, the solidification parameter is expressed as

$$G/R = \frac{T_m}{vx} \quad (2.3)$$

where T_m is the melting temperature, v is the welding speed and x is the distance between the heat source and the rear of the weld pool. The mentioned growth mode is important because it decides the size of grain structure. Theoretically, the weld metal grain structure can affect the mechanical strength. The formation of fine grain structure is preferable because it helps to reduce the solidification cracking during welding. Furthermore, it also improves the mechanical strength such as the ductility and fracture toughness.

Figure 2.9 Factors of growth mode during the solidification of weld metal [18].

Although the mechanism of microstructure development in the grain is complicated, the micro structural change of weld metal can be explained by using Continuous Cooling Transformation (CCT) diagram for low carbon steel based on the cooling rate (see Fig. 2.10). The hexagons show the cross sectional view of columnar dendritic grain in the weld metal. It can be seen that the final microstructure of weld metal depends on the cooling rate which is represented by the cooling curve shown in the diagram. After the weld metal is completely solidified, the microstructure is formed and one example of typical microstructure formation is shown in Fig. 2.11.

Figure 2.10 Continuous Cooling Transformation (CCT) diagram for weld metal [3].

Figure 2.11 (a) & (b) Typical weld metal microstructures in low carbon steel: A, grain boundary ferrite, PF (G); B, intragranular polygonal ferrite, PF (I); C, Widmanstatten ferrite; D, acicular ferrite, AF; E, upper bainite; F, lower bainite [3].

There are four factors which affect the microstructure development of weld metal: Cooling time, alloying additions, grain size and oxygen content. As shown in Fig. 2.12, considering the cooling rate slows down from curve 1 to 2 and then 3 with other factors

are fixed, the final microstructure can form from bainite to acicular ferrite and then sideplate ferrite (Widmanstatten ferrite). On the other hand, the decrease of oxygen content, increase of alloying additions and grain size will shift the microstructure regimes toward longer time and lower temperature with respect to the same cooling curve.

Figure 2.12 Effect of alloy additions, grain size and oxygen content on CCT diagram.

The HAZ refers to the area immediately outside the weld metal where the complete thermal cycle takes place. As shown in Fig. 2.13, the HAZ can be divided into three major sub-zones by grain structure: (1) Coarse grained zone; (2) Fine grained zone; (3) Transition zone. Grain growth occurs at the coarse grained zone where the parent metal is heated up to the critical temperature at 1200°C (for carbon steel). Since the temperature is close to the melting temperature, the grains are always “coarsened”. For the fine grained zone, the thermal cycle produces a smaller grain size than the one of the parent metal due to the temperature is lower than 1200 °C.

Figure 2.13 Different areas of HAZ.

From metallurgical point of view, the grain growth at the HAZ can affect the mechanical properties of the welded joint. Due to the bigger grain size in the coarse grained zone, it tends to have lower toughness strength. Therefore, the width of HAZ is very important. Theoretically, the width of HAZ must be kept as small as possible so that its micro structural change is small and negligible. For the types of microstructure, ferrite-phase field, bainite and martensite are commonly found at the HAZ because the peak temperature is lower than the melting temperature.

2.3 Operation of FCAW and Its Parameters

In this thesis, the FCAW was chosen to be the welding process due to the widely use of FCAW in manufacturing process. The operating principle of FCAW is shown in Fig. 2.14. Before the welding process is initiated, there is an air gap between the welding wire and workpiece. The current is not possible to pass through the air gap as air is not electrical conductive. When the wire is fed towards the workpiece, a short circuit is formed and the temperature rises. If the wire and workpiece is now separated for a few millimeters, the current is able to flow the heated gas and therefore the welding arc is formed according to

the previous section. This welding arc is sustained if the distance between the wire and the workpiece is kept relatively closed and constant.

Figure 2.14 Flux Cored Arc Welding Process.

For the shielding method, FCAW combines the use of flux and gas. The welding arc and metal transfer are shielded by the gas, which is dispensed from the nozzle surrounding the contact tube. As the welding torch travels along the welding path, the shielding gas is not able to cover the molten weld metal. Therefore, it requires other forms of shielding method to protect the molten metal. Like Shielded Metal Arc Welding, the slag is used to provide the protection. This slag is obtained from the flux which is filled inside the welding wire. When the molten flux is transferred to the workpiece together with the molten metal, it floats on top of the molten metal due to buoyancy force and forms a protective layer.

FCAW is a complicated process because it is affected by numerous operating parameters. In order to optimize the welding process, many researchers put in their efforts to find out the relationship between these parameters and the welding process. For an example, Lee *et al.* [25] and Raveendra *et al.* [26] used regression method to predict the welding geometry of Gas Metal Arc Welding. Chandel [27] also tried to correlate the operating parameters with the melting rate for Submerged Arc Welding by a mathematical modeling. He reported that higher current, longer free wire length, smaller diameter wire and electrode negative polarity can obtain greater melting rate while arc voltage and flux type has no significant effect. Based on the literature review, five important operating parameters: current, voltage, free wire length, welding speed and leading angle [28- 32] will be discussed in this section.

The current used for FCAW is normally direct current (DC). In fact, the alternating current (AC) is also used in some cases but it needs to be selected carefully. The selection of current types is based on the consideration of factors listed in Table 2.4. The table shows that only arc blow is the disadvantage of using DC. Basically, the magnetic field around the electrode is generated as the current flows through the welding wire and the base metal. This magnetic field tends to deflect the welding arc from its traveling path due to unbalanced magnetic field. In general, the back blow happens when welds toward the ground or the forward blow takes place in opposite direction. In fact, the forward blow should be avoided because it allows the molten slag to run forward under the deflected arc column. Therefore, lack of fusion and excessive weld spatter result.

The polarity of the welding wire for DC welding can be crucial in determining the depth of penetration. Fig. 2.15 shows that the welding wire with positive polarity can produce a deeper penetration. For the base metal, the heat generated at negative polarity (cathode) is

greater than the heat at the welding wire (anode). Therefore, the melting rate of base metal is higher. If the welding wire is negative polarity, the deposition rate of metal from welding wire is greater. In this case, more metal deposits to the base metal and causes the width of weld bead to be larger.

Table 2.4 Factors for the selection of current type.		
1.	Voltage Drop	Although the DC voltage drops more than the AC voltage in long welding cable, it can be compensated by increasing the voltage.
2.	Arc Starting	The arc initiation is easier with DC for small diameter of welding wire.
3.	Arc Length	The welding with short arc length (low arc voltage) is easier with DC than AC.
4.	Welding Position	DC is better than AC for vertical and overhead welding because of lower current is used.
5.	Arc Blow	The arc blow problem rarely happens for welding with AC because the magnetic field is balance due to the constantly reverse of polarity.

Figure 2.15 Weld penetrations for different electrode polarity [18].

Theoretically, the current is proportional to the wire feed rate if the welding wire diameter, composition and free wire length are unchanged. When the current is increased or decreased, the wire feed rate also changes accordingly in order to maintain the optimum ratio between the current and arc voltage.

In general, the effects of current are:

- (1) Increases the current to increase the metal deposition rate and penetration.
- (2) Excessive current produces convex weld surface with poor appearance.
- (3) Low current increases the droplet size but reduces the transfer rate.
- (4) Low current causes the weld to pickup excessive nitrogen and cause porosity.

Voltage, or arc voltage across the welding arc and arc length are also important in arc welding. As shown in Fig. 2.16, a welding arc in truncated cone shape is established in between the welding wire and the base metal. The length, ℓ , is referred to the arc length which defines the distance from tip of welding wire to the base metal.

For instance, this voltage can be expressed as [18]:

$$V = (V_c + V_a) + BI + \left(\frac{C}{I}\right)\ell \quad (2.3)$$

V_c and V_a mean the reduction of voltage at cathode and anode. The B is a constant value which is a function of the gas composition, pressure and the nature of welding wire. I is the current and C/I reflects the reduction of voltage per unit length of welding arc. Based on this equation, it is observed that voltage is proportional to arc length. Any variation of arc length requires the voltage to increase or decrease simultaneously. On the other hand, more than 80% of the total voltage drops at the anode and cathode over a very short distance (10^{-4} to 10^{-7} m). The sharp reduction of voltage is due to the electrical phenomena happens at the surface of welding wire and base metal.

Figure 2.16 Voltage and arc length [18].

The weld quality can be affected by the voltage. High voltage usually results in more weld spatter and irregular shape of weld because the arc length is longer. However, a narrow convex weld and poor weld penetration can be caused by low voltage.

The welding wire exposed from the contact tube to the tip of molten wire is defined as free wire length. According to Joule's Law, the heat is generated in the extended wire which is proportional to its length. Although the generated heat is insufficient to melt the metal, temperature at the extended wire can still affect the welding arc, metal deposition rate and weld penetration. Too long free wire length results into reduction of current and weld penetration, unstable welding arc and excessive weld spatter. On the other hand, weld spatter can build up at the nozzle if the free wire length is too short. Subsequently, shielding gas flow is choked and porosity may be created.

The welding speed affects the shape of weld and penetration. The weld penetration is usually deeper for low speed. However, too low in speed causes too much molten metal deposited in an area. The excessive weld pool tends to roll in front of the arc and

cushions the base metal. As a result, further weld penetration is difficult to occur. The over-heating of the base metal can also happen for low speed. It causes a rough appearance of weld with the possibility of trapping slag. On the other hand, too fast speed results in an irregular shape of weld bead.

The leading angle, θ , is measured from the vertical line in the plane to the weld axis. Fig. 2.17 and 2.18 shows the welding position in “horizontal” and “vertical” separately. When the welding torch is pointed to the direction of torch traveling, the welding is in “push” direction. If the welding torch is pointed in the opposite direction, it is defined as “pull” direction. In fact, the sign of leading angle with different welding direction is used to determine the direction of arc force to be applied to the weld pool. For “push” welding, the arc force pushes weld pool to move forward. Therefore, weld penetration is reduced but the height of weld bead is increased. On the other hand, the “pull” welding is most widely used for FCAW. Basically, the weld pool tends to flow in front of welding arc, which forms a buffer between the welding arc and base metal. This buffer is able to melt the base metal further so that the weld penetration can be further increased.

Figure 2.17 Horizontal weld positions [18].

Figure 2.18 Vertical-up weld positions [18].

The value of leading angle depends on the base metal thickness and weld position. For horizontal position, the leading angle ranges from 2° to 25° . On the other hand, the leading angle for vertical position is only 5° to 10° . Too large angle can reduce the effectiveness of the shielding gas and cause irregular shape of weld bead.

Maintaining these operating parameters with optimum combination is crucial because it can affect the weld quality significantly. However, controlling of them is not easy especially in manual welding because most of the parameters such as welding speed, free wire length and leading angle are depended on the welder. Therefore, the weld quality can be badly affected if the welder's skill is not properly trained. The welder's skill can be defined by the voltage and current setting, welding speed to be used, stability of hand and holding position of welding torch at different welding position. After the welder's skill is properly developed, good weld quality can be ensured.

2.4 Types and Causes of Weld Defects

A classification of the weld defects and their possible causes based on their nature of occurrence are shown in Table 2.5. Lack of fusion refers to the metal fusion which is not completely done. It is usually found at the joint boundaries or between passes. For slag inclusion, it really means the entrapment of slag or nonmetallic particles in the weld. Since these two defects can only happen inside the weld, they are usually detected by using NDT methods. The same quality inspection methods are also used for the measurement of porosity and internal crack. In fusion welding, porosity is defined as cavity type of defects due to the gas entrapped inside the weld. For internal crack, it can be a result of opening displacement which is caused by hot or cold crack. On the other hand, overlap, undercut and blow holes are easier to measure because they can be observed on the surface of welds. Overlap is the protrusion of weld while undercut is the unfilled groove at the toe or root of the weld. Blow hole is also cavity type of defect which appears on the surface of weld. In order to show the location of different weld defects, a single pass bevel-groove weld with various defects is presented in Fig. 2.19.

Figure 2.19 Location of weld defects for single pass bevel-groove weld joint [6].

Table 2.5 shows that most of the weld defects are due to multiple causes. For an example, the porosity can be caused by the excessive gas entrapped inside the weld. The source of excessive gas can be either internal or external. Oxygen, hydrogen and nitrogen are the major internal sources of gases which are dissolved in the molten weld metal. Oxygen may enter the weld pool as oxides on filler metal or base metal. Hydrogen is introduced into the weld pool by the dissociation of water which is in the form of moisture in flux or on the base metal surface. Nitrogen can be present in the contaminated shielding gas. For the external source of gas, it refers to the air entering into the welding arc from atmosphere as a result of poor gas shielding. Therefore, identifying the root causes of the weld defect is tough and time consuming.

Table 2.5 Types and causes of weld defects [6].		
	Types of defects	Possible causes
Welding imperfections	Lack of fusion	- Wrong joint design contributing to lack of access to all faces of the weld joint. - Insufficient current. - Improper pre-weld cleaning.
	Slag inclusion	- Faulty welding technique. Sharp notches in joint boundaries or between weld passes causes slag entrapment in the weld metal.
	Overlap	-Wrong selection of welding material. - Improper preparation of base metal. - Incorrect welding procedure.
	Undercut/Underfill	- Improper weld technique. - Excessive current. - Higher heat concentration.
	Blow hole	- Improper weld technique.
Metallurgical imperfections	Porosity	- Improper initiation or termination of the welding arc. - Excessive gas in welding atmosphere.
	Hot crack	- Internal stress.
	Cold crack	- Associated with hydrogen embrittlement.

2.5 Quality Assurance of Welding

Some of the quality inspection methods such as Destructive Testing (DT) and Non-destructive Testing (NDT) have been introduced in previous chapter. However, the real world application of these methods is constrained due to their inherent limitations. In

order to achieve high performance of weld quality assurance, the features of future quality inspection method are identified as:

- (i) Real-time.
- (ii) In-situ.
- (iii) Accurate.
- (iv) Easy to use.
- (v) Cost effective.

In the followings, the fundamental of the DT and NDT methods are presented and compared in order to examine their limitations and later emphasize on the motivation for developing a real-time monitoring and diagnosis method for weld quality.

2.5.1 Destructive Testing

To inspect the weld quality, DT methods are usually used for obtaining mechanical, chemical and metallurgical properties of welded joints, locating the weld defects and qualifying welding procedures and welders. Basically, the common tests conducted under DT methods are tensile, bend, impact and hardness testing. Other tests like fatigue, corrosion and creep-rupture test are also used to determine special properties.

Tensile testing is the most fundamental type of mechanical test. It is simple and inexpensive. By stretching the specimens in one direction, the mechanical properties such as yield strength, ultimate tensile strength, modulus of elasticity and strain can be obtained. The test is carried out on a rectangular cross section specimen from a multi passes butt joint. The specimen is oriented across the welded joint which includes the base metal, heat-affected zone and the weld (as shown in Fig. 2.20). After the specimen is stretched until breaking into two pieces, the mechanical properties are obtained. British

Standard [33] provides international standards for the test mentioned above. Basically, the tensile strength of the welded joint has to be higher than the base metal so that the failure occurs either in the base metal or the heat affected zone. In case of poor welded joint, some special designs have to be made in order to compensate for the loss of strength.

Bend testing is used to measure the ductility of welded joints in order to meet the requirements of specific forms or shapes. For an example, it requires the specimen to be bent 180° into a “U” shape around a standard plunger. Fig. 2.21 shows the commonly used guided test. The requirements of such bend test are specified in welding qualification specification [34]. Based on the testing result, weld defects can be revealed by the extensively plastically deformation of the specimen.

Figure 2.20 Specimen for tensile testing.

Theoretically, the toughness is defined as the amount of energy required to cause the material to fracture. It is used to evaluate the ability of the welded joint for service at different temperature level. The most commonly used type of test is the Charpy V-notch impact test (as shown in Fig. 2.22). The specimen is in the form of a notched beam. The notch can be created at the base metal, weld metal or heat-affected zone. In order to carry out the test, the specimen is supported by the anvil at two ends and struck at a point opposite to the notch by a swinging pendulum. The amount of energy used to break the notched specimen is the toughness at the test temperature. For the specification of test, it can be found in the BS Standard [35].

The hardness of welded joint means that its resistance to indentation. Basically, Brinell and Vickers Hardness testing are the commonly used hardness testing. Brinell hardness testing is carried out by forcing a hardened steel ball into the surface of specimen using a specified load for a period of time. After the steel ball is retracted, the diameter of the impression is measured in order to obtain the Brinell Hardness Number (BHN). In practice, Brinell hardness testing is used for bulk metal because bigger ball diameter cannot be used to measure the hardness variation across a welded joint.

The operation of Vickers hardness testing is similar to the Brinell testing but the major difference is the use of a square based pyramidal diamond indenter instead of a hardened steel ball. At extremely high load, the depth of impression created by the diamond made indenter is not deformed and therefore it is able to ensure the accuracy of testing for very hard material and small area at the welded joint or heat-affected zone. As shown in Fig. 2.23, the load is applied to the indenter by a simple weighted lever. After the two diagonals, d_1 and d_2 are measured and averaged (seen in Fig. 2.24), the value is divided by the applied load in order to obtain the Vickers Hardness Number (DPN). Both testing procedure can be found in the references [36, 37].

Figure 2.22 Charpy V-notch impact test.

Figure 2.23 Schematic diagram of Vickers hardness testing.

Figure 2.24 Indentation of Vickers hardness testing.

Metallurgical Test is mainly used to determine:

- (i) Number of weld passes.
- (ii) Depth of penetration of a weld.
- (iii) Metallurgical change of material in the weld metal and HAZ.

Basically, it involves Macro and Micro Testing. For Macro Testing, it is done by visual inspection on the cross sectional view of workpiece so that weld defects such as pores, slag inclusions and cracks can be identified. However, the observation of Micro testing is done by using microscope which the magnification is at least 50 times and above. Therefore, it is able to reveal the microstructure of base metal, HAZ and weld metal. For both testing, samples have to be prepared by cutting the workpiece at desired location, grinding, polishing and etching of cut surface to reveal the detail of welded joint.

2.5.2 Non-destructive Testing

Non-destructive testing (NDT) refers to the inspection methods which are used to evaluate the quality of a workpiece without destruction. Since the workpiece is not destroyed and yet the result of testing is highly reliable, these inspection methods are very important because both cost and time in product evaluation and troubleshooting can be reduced significantly. In practice, Ultrasonic Test, Radiographic Test and Eddies Current test are most commonly used. Others methods such as spectroscopic analysis, acoustic emission, infrared sensing and metal transfer monitoring methods are currently under research and development phase. In the followings, all these methods will be discussed to present the current state-of-art technology in developing real-time monitoring and diagnosis methodology for weld quality.

Ultrasonic Test is very useful to detect the weld defects such as internal cracks, laminations, porosity, slag inclusion and lack of fusion. Basically, the precise position and depth of weld defects can be measured because the velocity of sound transmitting through a material is nearly constant, which makes it an accurate measurand for distance. Furthermore, the amplitude of reflected sound pulse is nearly proportional to the size of defect. Therefore, it becomes the most important and widely used NDT method to evaluate weld quality. The advantages of Ultrasonic Test are shown as:

- (i) High penetrating power to allow the detection of defects in thick sections.
- (ii) High sensitivity to small defects.
- (iii) Capable to determine the location and size of the defects.
- (iv) Portable equipment can be used on site.
- (v) Non-hazardous to personnel and other equipments.

However, Ultrasonic Test is not suitable for real-time inspection due to:

- (i) Rough, irregular in shape, very small or thin and not homogenous material is difficult to use.
- (ii) Surface must be clean.
- (iii) Couplant is essential to provide effective wave energy transmission between transducer and test piece.

Many researchers have tried hard in order to improve the capability of Ultrasonic Test. Stares *et al.* [38] tried to implement a complicated real-time monitoring system based on Ultrasonic Test for MIG welding. It consists of a transmitting and receiving transducer at 74mm apart, a linear encoder to control the acquisition of ultrasonic data and a digital instrument to process the raw data. Similar work was repeated by Chen [39] for wire bonding. On the other hand, Fujitma *et al.* [40] reported a real-time quality monitoring method by using line-focused ultrasonic probe for resistance spot welding. Unfortunately, they are too complicated to implement and therefore not suitable for online implementation.

Radiographic Test uses x-rays or gamma rays to penetrate into the workpiece to detect the weld defects by the image recorded on film. The image on film is 2 dimensional projection of the workpiece due to the varying densities of radiation at different scanned area. A good quality of radiographic image is highly depended on the skilled radiographer because the radiographic contrast and definition need to be adjusted correctly. Furthermore, the possibility of radiation exposure can be a serious health hazard to the operators. Therefore, only certified radiographers are allowed to perform the test in order to take care of the safety.

Radiographic Test is crucial in some cases where Ultrasonic Test is difficult to use. For an example, a very rough surface or odd shape of workpiece is almost inaccessible by the ultrasonic transducer but it can be examined by Radiographic Test because the test is carried out without touching the surface of test piece.

For real-time monitoring of weld quality, Warren *et al.* and Liao *et al.* [41, 42] developed an automated radiographic NDT system which consists of digitization of radiographic image and feature extraction of linear weld based on the intensity plot of radiographic image. To improve the accuracy of feature extraction of radiographic image, pattern recognition and classification such as Artificial Neural Network (ANN) is used [43- 45]. Since the method is only applicable to linear but not curve weld such as piping joints, the use of this method is limited. Furthermore, the safety is another important problem to be resolved carefully as the radiation is harmful to the operators.

Eddy current test is achieved by the eddy current flow which is induced in the workpiece. Weld defects can be detected by the nearby coil as a disturbance to the flow of eddy current. Basically, this eddy current is induced based on the principle of electro-magnetic induction phenomenon. When AC current flows through a conductor such as copper wire, a magnetic field is generated in and around the conductor. If another conductive conductor is moved near to its close proximity, current is induced in the second conductor. This current is called “Eddy” because the current flows in a circular path.

One of the major advantages of Eddy current test is the variety of inspections that can be performed. It can be used for seamless and welded piping and tubes inspection, material and coating thickness measurement, material conductivity measurement and etc. The other advantages are shown as:

- (i) Sensitive to small cracks.

-
- (ii) Surface and near surface defects can be detected.
 - (iii) Test probe can be contactless to the workpiece.
 - (iv) Minimum workpiece preparation is required.

In order to obtain the induced eddy current, the workpiece has to be conductive material. On the other hand, the eddy current density also decreases gradually along the depth of penetration. This characteristic of eddy current limits the test from deep penetration testing. Furthermore, the distance between the test probe and workpiece has to be held constant in order to have an accurate result. Therefore, a certified operator is required to perform the Eddy current test.

Similar to Ultrasonic Test, the use of eddy current for real-time quality monitoring is not seen until the report published by Smith *et al.* in 1985 [46]. However, the proposed method is impractical because the system consists of a sophisticated computer controlled scanning device and the result is only mathematically fitted data with raw eddy current signal.

2.5.3 Monitoring of Metal Transfer

The metal transfer of consumable arc welding has drawn plenty of attention in recent years because it is found to be closely related to the dynamic change of welding process. In 1974, Stephan [47] started with the experiments to evaluate the surface tension and lorentz effects on the weld droplet. In order to quantify the metal transfer, Lordacescu [19] classified it into different metal transfer modes. Furthermore, the importance of metal transfer mode in welding was discussed.

In order to study the relationship between metal transfer modes with weld quality, there are four major types of force-based models to be used: Static force balance model (SFBT), pinch instability theory (PIT), volume of fluid method (VOF) and heat transfer theory. For the SFBT, the size of droplet is determined from the state of force balance at the droplet based on the buoyancy force, electromagnetic force, drag force and surface tension force [48, 49]. The PIT considers the instabilities of droplet in an infinite cylindrical column due to the magnetic pinch force [50]. However, both methods can only provide an approximate description of droplet formation because the wire feed rate and shielding gas composition are not considered in the models [51]. For the VOF model, it is an improved numerical model based on the SFBT and PIT. In the VOF model, the momentum flow of the molten metal inside the droplet is included [52]. Although the predicted result agrees with the experimental results over a wide current range, the calculation is very complicated and time consuming [53].

Recently, Hu *et al.* [54] revealed that the metal transfer mode is not only depended on the forces but also the heat transfer within the droplet and weld pool. The instantaneous heat flow within the welding wire, welding arc and weld pool can affect the formation of droplet and hence the metal transfer mode. Therefore, the inclusion of heat transfer model is important.

Modeling of the heat transfer in arc welding has been developed for the past decades. Kumar *et al.* [55] created a three dimensional model to predict the transient temperature distribution for GMAW. He found that both kinetic energy and heat content of metal droplet are important in shaping the weld bead and penetration. Kim *et al.* [56] studied the heat transfer and fluid flow phenomena in the weld pools together with the effects of four common forces by commercial software. On the other hand, the effect of

impingement of droplets on the weld pool was investigated [57]. It was found that the impinging momentum is finally damped out and has no influence on the weld penetration. More types of numerical models have been developed to describe the relationship between the acting forces, heat transfer and fluid flow pattern with the metal transfer mode and subsequently the dynamic weld pool such as free surface profile, temperature distribution and velocity field [58– 62].

Apart from determining the metal transfer mode by numerical modeling, some physical measurement approaches were carried out. A measurement system, which consists of laser as light source, optical lenses, optical fiber and high speed camera, was designed to measure the size and transfer rate of droplet [63]. During the welding process, the droplet images were sampled and corrected on video tape. Therefore, the desired results can be obtained from the video tape by counting the number of droplets per second and measuring the size of droplet directly. On the other hand, the metal transfer was also determined by spectrum analysis based on the arc light emission [64]. However, both methods are difficult to implement due to the alignment of optical lenses.

2.5.4 Other Real-time Inspection Methods

Recently, the real-time inspection by means of emission spectrometry analysis was discussed [65]. Basically, the spectrometry refers to the measurement of the electromagnetic spectrum which results from absorption, emission or diffraction of electromagnetic radiation by atoms or molecules. Since the welding arc is in an energy steady state, the atoms or molecules can be characterized by discrete amount of energy. When a change of energy state occurs in an atom or a molecule, it is generally accompanied by the emission or absorption of light with certain wavelength. Such wavelengths provide

very useful information on thermodynamic and quantum parameters which are necessary for calculating the plasma properties like electronic temperature and density. After the correlation between the weld quality and the extracted features based on the spectrum result is established, the real-time monitoring of weld quality can be achieved.

To further extend the use of this method, different algorithms have been proposed and tested in order to extract the features. Standard deviation of the estimated Kalman filter [66] and linear phase operator sub-pixel algorithm [67] are used for the feature extraction of electronic temperature. Besides electronic temperature, special wavelength such as UV and infrared emission [9, 68, 69] are also measured and correlated with the weld defects. These spectrum analysis based monitoring methods are non-contact because the plasma or optical emission is collected by the collimator. Furthermore, the monitoring process can be performed in real-time if the pattern recognition and classification part is computerized. However, the cost of installing such measurement system which consists of the collimators, optical fiber and spectrometer can be very expensive and not suitable for harsh environment.

Another type of signal used for weld defects detection is acoustic emission during welding process [70, 71]. Basically, the acoustic waves are generated and varied according to the oscillations of metal transfer. Since the operating parameters such as voltage, current, free wire length, flow rate of shielding gas and welding speed can affect the oscillations of metal transfer, the acoustic waves are capable to reflect any abnormal change of these operating parameters. This has been confirmed by experimental results which the acoustic spectrum decomposed into respective frequency range is correlated with the weld defects. However, the accuracy of using this method is not satisfactory

because the acoustic signal is easily affected by the background sound in the industrial environment.

CHAPTER 3

QUALITY MONITORING OF ARC WELDING

Considering an electrical circuit, its input electrical impedance is an inherent system property. The resistance and reactance of impedance provides rich information which are correlated with the operating parameters and hence the weld quality. In this Chapter, a more accurate heat input per unit length is proposed based on the resistance of impedance. By employing this heat input per unit length and resistance of impedance as monitoring signatures, real-time monitoring and diagnosis of weld quality is achieved. The experimental results confirmed the findings by comparing the resistance of impedance with the conventional resistance which is calculated using Ohm's Law. Further comparison was also made in between the heat input per unit length obtained by the conventional and proposed method.

3.1 Input Electrical Impedance of Arc Welding

As shown in Fig. 3.1, the arc welding consists of a welding torch, welding wire, welding arc and base metal. Due to the complexity of welding process, the important welding parameters such as voltage, current, arc length and etc are varying with respect to time. Such dynamic behavior is known as time-varying system. In order to reflect the dynamic behavior of arc welding, an equivalent circuit which consists of a resistor (R), inductor (L) and capacitor (C) connected in series is then employed because they form the input

electrical impedance which is capable to reveal the time-varying system properties of welding.

Figure 3.1 Arc welding process and its equivalent circuit.

The input electrical impedance, $Z_{in}(t)$ of the circuit is obtained easily by measuring the input voltage and current simultaneously at the input port of system. Conventionally, the computation of $Z_{in}(t)$ is carried out by applying Fourier Transform to the input signals and later calculating the result in frequency domain. However, it is not suitable to use this method because the result does not reflect the $Z_{in}(t)$ in real-time. Since the input voltage and current are always supplied at single frequency, the method of Hilbert Transform (HT) is employed to compute the time-varying $Z_{in}(t)$.

Hilbert Transform (HT) of a real-valued time domain signal, $x(t)$, is denoted as $\tilde{x}(t)$ which yields the original signal in its analytical form, $\hat{x}(t) = x(t) + j\tilde{x}(t)$. Although the analytical signal is defined as a magnitude function $A(t)$ and an instantaneous phase function $\theta(t)$, it is quite different from the Fourier Transform of $x(t)$ in its complex-valued frequency domain signal $X(\omega)$. The main difference is that both magnitude and phase are functions of time, which means that they not only provide the information in frequency domain but also vary with time. This feature is especially important to obtain

the $Z_{in}(t)$ because it is capable to provide the time-varying system properties of arc welding.

The detail of HT can be found in [72]. Theoretically, the HT for any raw signal can be defined as:

$$\tilde{x}(t) = h[x(t)] = \int_{-\infty}^{\infty} \frac{x(u)}{\pi(t-u)} du \quad (3.1)$$

Basically, the $Z_{in}(t)$ can be obtained by taking the quotient of input voltage to current which are firstly converted into analytical form (see Eq. 3.2 – 3.4):

$$\hat{V}(t) = V(t) + \tilde{V}(t) \quad (3.2)$$

$$\hat{I}(t) = I(t) + \tilde{I}(t) \quad (3.3)$$

$$Z_{in}(t) = \frac{\hat{V}(t)}{\hat{I}(t)} = Z_r(t) + j\omega Z_x(t) = |Z_{in}(t)|e^{j\omega\phi(t)} \quad (3.4)$$

$$Z_{in}(t) = R(t) + j\left(\omega L(t) - \frac{1}{\omega C(t)}\right) \quad (3.5)$$

Equation (3.4) and (3.5) show that the $Z_{in}(t)$ can be presented either in polar form ($|Z_{in}(t)|$, $\phi(t)$) or complex form ($Z_r(t)$, $Z_x(t)$). The $|Z_{in}(t)|$ and $\phi(t)$ is the magnitude and phase of $Z_{in}(t)$ whereby the $Z_r(t)$ and $Z_x(t)$ is the real part and imaginary part, or the resistance and reactance of $Z_{in}(t)$. For the convenience of presenting the $R(t)$, $L(t)$ and $C(t)$, the complex form of $Z_{in}(t)$ is used in this research. Basically, the $Z_r(t)$, or $R(t)$ is the resistance of arc welding which converts the input electrical power into heat to melt metal. The $L(t)$ and

$C(t)$, however, are related to the welding arc which some of the input electrical power is conserved in the reactance without dissipated as heat energy.

Fig. 3.2 and 3.3 illustrates a typical time record result of resistance and reactance of impedance for a bead-on-plate weld. In theory, the selection of sampling rate and sample period has to satisfy the Sampling Theorem [73]:

- (1) Sampling Theorem I. The sampling rate must be more than twice the highest frequency of measured signal.
- (2) Sampling Theorem II. The sample period remains an integer multiple of the total data points with the time interval.

In this case, the sampling rate used for acquiring the input signals is 3k Hz because the highest frequency of measured signals is about few hundreds Hz based on the observation of measured signals. Furthermore, the sample period is set to 20s. Therefore, total number of data points shown in the graphs is equal to 60k (20s x 3k Hz). The sample period is also long enough to capture the required information during welding process.

At the beginning of weld, the high jerk of both curves is caused by the unstable welding conditions during weld initiation. The formation of welding arc and unsteady metal melting at the tip of welding wire can be the reasons attributed to the large amount of change for both curves. Once the welding arc is formed and the metal melting is steady, both curves show periodically oscillation at certain frequency. The resistance is observed to be positive value because it is proportional to the free wire length and arc length of welding. However, the reactance oscillates at zero as a result of energy exchange between $L(t)$ and $C(t)$. In the followings, a series of experiments were carried out in order to confirm the relationship between the $Z_{in}(t)$ with the operating parameters.

Figure 3.2 A typical time record result of $Z_r(t)$.

Figure 3.3 A typical time record result of $Z_x(t)$.

3.2 $Z_{in}(t)$ Dependency on Operating Parameters

In order to investigate the relationship between the operating parameters with the $Z_{in}(t)$, a study on the effects of operating parameters was carried out. Five important factors: voltage, current, welding speed, free wire length and leading angle are included in the experiments. Table 3.1 lists the parameter setting for each factor. Each group of the experiments was repeated for 6 times in order to confirm the repeatability of result. For other operating parameters, CO₂ was used as the shielding gas and the gas flow rate was fixed at 20L/min. The welding wire was flux-cored, diameter 1.2mm and its feed rate was automatically set by the wire feeder which is proportional to the current. For the welding process, only FCAW was involved to make horizontal bead welds on 10mm thickness carbon steel plate, grade AH36.

As shown in Fig. 3.4, the welding torch was attached to a 2-axis Cartesian Robot so that the free wire length and welding speed can be controlled. This welding torch was also connected to a contact relay for the weld to start by automated triggering. In order to hold the welding torch and control the leading angle, a 360° rotational torch holder with heat isolator pad made by ceramic material was designed and built. Furthermore, a steel table was constructed for mounting the robot and placing a workpiece. The detail design of the torch holder and steel table can be found in Appendix A. For the actual experimental setup, it can be observed in Appendix B.

Bead-on-plate test [74] was adopted in order to standardize the workpiece preparation. Fig. 3.5 presents the suggested dimensions of the weld beads on plate. Basically, 4 weld beads were made on the steel plate and they were kept 30mm apart. The length of weld bead, d was depended on the welding speed and welding time which is fixed at 20s of

weld. The portion of 20mm weld bead at the beginning and end of weld were discarded to avoid unsteady result.

For the acquisition of voltage and current signal, voltage probe (Tektronix, P520) and current probe (Hioki, 3285) was used to measure the signals simultaneously. These input signals were sampled by a 12 bits, 8 channels DAQ system (National Instrument, SCXI-1305, 1000 & DAQCard-6062E) at 3 kHz. A built-in analog filter with 100Hz cut-off frequency was used for each channel to prevent signal aliasing (see Appendix B). Following up the calculation steps shown in the previous section, the $Z_{in}(t)$ can be computed easily by using MATLABTM.

Taking the result shown in previous section as an example, the weld was done based on the setting in the first row of Table 3.1. Since the welding speed is 10 mm/s and total welding time is 20s, the acquired signals at the first and last 2s were abandoned. Therefore, the remaining portion which is equivalent to 48k data points were then processed to compute the mean and standard deviation values according to Eq. (3.6) and (3.7).

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i \quad (3.6)$$

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2} \quad (3.7)$$

where $\bar{x}$ and σ is the mean and standard deviation for individual result. The N refers to the total numbers of data points used for the computation.

Table 3.1 Setting of operating parameters for welding parameters study.				
Voltage(V)	Current(A)	Welding Speed(mm/s)	Free Wire Length (mm)	Leading Angle (deg)
25	200	10	15	15
20	200	10	15	15
35	200	10	15	15
25	130	10	15	15
25	300	10	15	15
25	200	5	15	15
25	200	15	15	15
25	200	10	5	15
25	200	10	25	15
25	200	10	15	0
25	200	10	15	30

Figure 3.4 Schematic diagram of experiment setup.

Figure 3.5 Schematic diagram of weld beads on plate.

Fig. 3.6 illustrates the mean and standard deviation of $Z_r(t)$ and $Z_x(t)$ for 3 different groups of operating parameters setting. Each group includes 6 repeated operating points. When comparing between the $Z_r(t)$ and $Z_x(t)$, it is observed that the mean of $Z_x(t)$ is always zero. The reason is due to the energy exchange between the $L(t)$ and $C(t)$ as mentioned above. On the other hand, the standard deviation of $Z_x(t)$ is almost the same as standard deviation of $Z_r(t)$. This implies that the amplitude of $Z_r(t)$ and $Z_x(t)$ under periodic change condition is exact.

Figure 3.6 Mean & standard deviation plot for (a) & (b): voltage; (c) & (d): current; (e) & (f) welding speed; (g) & (h): free wire length; (i) & (j): leading angle. (a), (c), (e), (g) & (i) are plotted for $Z_r(t)$. (b), (d), (f), (h) & (j) are plotted for $Z_x(t)$.

Based on the results of $Z_r(t)$, the comparison between different groups of operating parameters also reveals several important findings. The mean of $Z_r(t)$ increases while the voltage or free wire length is increasing. On the other hand, increment of current causes the mean of $Z_r(t)$ to decrease. These observations are true because the $Z_r(t)$ is indeed the resistance of welding and therefore it varies according to Ohm’s Law. However, no significant change of welding speed and leading angle is observed for the mean of $Z_r(t)$.

The standard deviation of $Z_r(t)$ is correlated with the stability of welding arc since the $Z_r(t)$ is proportional to the arc length. Small value of standard deviation shows less change of arc length and therefore the welding arc is more stable. The observations for different groups of operating parameters show that higher voltage or faster welding speed reduces the standard deviation of $Z_r(t)$ but larger current, leading angle or longer free wire length causes the welding arc to be unstable.

In conclusions, all the operating parameters involved in the experiments have effects on the $Z_{in}(t)$. Voltage, current and free wire length influence both mean and standard

deviation of $Z_r(t)$ while welding speed and leading angle only affect the standard deviation of $Z_r(t)$. Furthermore, only higher voltage and faster welding speed have positive effect on the welding arc but the increment of other operating parameters affects the stability of welding arc. Other observations also show that the mean of $Z_x(t)$ is always equal to zero and the standard deviation of $Z_x(t)$ is very closed to the standard deviation of $Z_r(t)$. The established relationship between the operating parameters and $Z_{in}(t)$ is important because they provide a foundation for the operating parameters selection and the feature extraction from $Z_{in}(t)$.

3.3 Features of $Z_{in}(t)$ for Monitoring Weld Defects

According to Chapter 2, the heat input per unit length is an important feature for weld quality monitoring. By definition, it is used to compute the heat being consumed to melt the welding wire and base metal in order to form the welded joint. However, Eq. (2.2) reveals that only input electrical power (V multiplied by I) is involved in the computation. In this case, this assumption is true when only resistor is presented in the circuit and converts the input electrical power into heat. As shown in Eq. (3.8), the Joule's Law states that heat is generated when electrical current flows through a resistor. If only resistance exists in the circuit, the heat generated is actually equal to the input electrical power by substituting Eq. (3.9) into Eq. (3.7).

$$h(t) = I^2(t)R(t) \quad (3.8)$$

$$R(t) = \frac{V(t)}{I(t)} \quad (3.9)$$

Fig. 3.7 shows that the self-induced magnetic flux is generated around the welding arc as result of current flow. Furthermore, the capacitance is found in the welding arc because there is a reduction of voltage measured in the ionized gas region. This confirms that the equivalent electrical circuit of arc welding does not only consist of resistance but also inductance and capacitance. Therefore, Eq. (2.2) is no longer accurate. For accurate computation of heat input per unit length, the Eq. (3.10) or (3.11) should be used.

Figure 3.7 Electrical behavior of arc welding process.

In the case the arc travels from s_a to s_b over a period from t_a to t_b , the average heat input per unit length over the traveled distance is

$$\bar{h} = \frac{\int_{t_a}^{t_b} h(t) dt}{s_a - s_b} \quad (3.10)$$

or

$$\bar{h}(t) = \frac{\sum_{k=a}^b I_k^2 Z_{r,k}}{s_a - s_b} \times \Delta T \quad (3.11)$$

where k indicates the sequence of the data in the record, $Z_{r,k}$ is the resistance of impedance in sequence and ΔT is the period of time defined by the t_a to t_b . Since the $Z_{r,k}$ is measured precisely as compared with the conventional resistance calculated by Ohm's Law, the $\bar{h}$ is therefore very accurate. On the other hand, the $\bar{h}$ will be a continuous time record if the ΔT is selected small enough. Therefore, the $\bar{h}(t)$ which varies along time is obtained. As shown in Fig. 3.8, each point in the curve represents the average heat input over a period of 0.1 seconds (which is the average over 300 data points over time).

Figure 3.8 A typical time record of $\bar{h}(t)$.

According to the literatures, the arc length is an important factor which is related to welder's skill. The fluctuation of arc length can be very severe if the welder is not properly trained to control the free wire length. Since the $Z_r(t)$ is proportional to the arc length according to Ohm's Law, it can be employed as an important feature for weld quality monitoring.

3.4 Dependency of Heat Input per Unit Length on $Z_r(t)$

It is essential to confirm that the proposed method for average heat input per unit length calculation is valid. Therefore, experiments were carried out according to the parameter setting shown in Table 3.2. Basically, each group of the experiments was repeated for 5 times in order to obtain the experimental results. The experimental setup is the same as shown in Fig. 3.4. Other operating parameters are kept constant: free wire length = 15mm; leading angle = 15°; flow rate of CO₂ shielding gas = 20 L/min.

Table 3.2 Setting of operating parameters for the investigation of $\bar{h}(t)$.		
Welding Parameters		
Voltage(V)	Current(A)	Welding Speed(mm/s)
24	150	4
28	150	4
24	200	4
28	200	4
24	150	7.5
28	150	7.5
24	200	7.5
28	200	7.5
26	175	5.75

Fig. 3.9 shows a typical example based on the difference between the conventional resistance (R) and $Z_r(t)$ in term of percentage. It can be seen that the difference of resistance can be higher than 200% for instant result. This difference is crucial especially in real-time monitoring because it will lead to wrong diagnosed result and therefore the weld defect cannot be detected accurately. Furthermore, the conventional resistance

cannot be correlated with the arc length since it contains so much error due to the incorrect calculation method.

Another example of comparison between the conventional and proposed method for average heat input per unit length calculation is shown in Fig. 3.10. It is observed that the $\bar{h}(t)$ is always lower than the conventional one. This is true because the $\bar{h}(t)$ computes the true heat generated and used for welding but not the total input electrical power. All the experimental results are listed in Appendix C. Basically, the $\bar{h}(t)$ is lower by 3 - 97J per unit length. Fig. 3.11 reveals that larger difference in heat input per unit length is always observed for higher current. However, higher voltage causes small difference in value. The reason can be due to that higher current induces more magnetic flux which increases the inductance. For the capacitance, it is inversely proportional to the voltage. Therefore, the energy being stored in the $Z_x(t)$ is lesser.

Figure 3.9 Difference of resistance in percentage.

Figure 3.10 Comparison of typical $\bar{h}(t)$ based on the proposed and conventional method.

Figure 3.11 Comparison of $\bar{h}(t)$ in percentage based on the experiment groups.

The presented results confirm that the proposed average heat input per unit length is accurate to compute the actual heat being generated and used for welding. The difference between the $Z_r(t)$ and conventional resistance (R) really implies that the equivalent circuit of arc welding does not only consist of resistor but also inductor and capacitor. On the

other hand, the comparison between the conventional and proposed heat input calculation further confirm the existence of inductance and capacitance. In the next chapter, the importance of $\bar{h}(t)$ and $Z_r(t)$ will be further discussed and later they are employed as the monitoring signatures for real-time monitoring and diagnosis of weld quality.

CHAPTER 4

DEVELOPMENT OF A $Z_{in}(t)$ – BASED WELD QUALITY MONITORING & DIAGNOSIS SYSTEM

In this chapter, a new method for real-time monitoring and diagnosis of weld quality is introduced by employing $\bar{h}(t)$ and $Z_r(t)$ as the monitoring signatures. As compared with other NDT methods, the proposed method is real-time, low cost, robust and more importantly, it provides a simple diagnosed result which the causes of weld defects are classified by abrupt change of $Z_r(t)$ or wrong welding speed. The capability of the proposed method is confirmed by conducting a validation test to compare with two well known quality inspection methods – Ultrasonic Test and Macro Testing. At the end of this chapter, a prototype of real-time quality monitoring and diagnosis apparatus for FCAW has been developed and presented.

4.1 Monitoring & Diagnosis Strategy

The concept of carrying out the monitoring and diagnosis process of weld quality is logically illustrated in Fig. 4.1. For monitoring process, the $\bar{h}(t)$ is firstly employed as the monitoring signature. According to the literatures [75, 76], the heat input has to be controlled within a specific range so that the weld quality is assured. Therefore, in this

research, the $\bar{h}(t)$ is computed and monitored continuously in order to ensure that it is within an optimum range called “Pass-Band”. This “Pass-Band” is defined by 2 constant values, Upper Control Limit (UCL) and Lower Control Limit (LCL). If the $\bar{h}(t)$ is out of “Pass-Band”, possible weld defect is detected.

Figure 4.1 Monitoring and diagnosis process of weld quality.

In order to carry out the monitoring process, the value of UCL and LCL has to be found so that the “Pass-Band” is identified. In this case, an experimental work based on well-known Design of Experiment technique-Taguchi Method was done. This technique is used in such a way that the maximum information about the optimum range of $\bar{h}(t)$ can be extracted from a minimum experimental work. The detail of identifying the “Pass-Band” is discussed in the following section.

As mentioned in Chapter 2, there are various types of quality inspection methods to be used for examining the weld quality. In this research, both Macro Testing (MT) and Ultrasonic Test (UT) are selected as the DT and NDT methods to confirm the weld

quality. After the weld quality results are obtained, they are compared with the $\bar{h}(t)$ at the corresponding location in order to show the correlation between the $\bar{h}(t)$ with the weld defects.

According to the current method used for weld defect classification, the geometry of weld defects is employed because it directly relates to the failure of weld joint. As shown in Chapter 2, the classification of weld defect is rather complicated due to the various shape and size of weld defect. Furthermore, those weld defects are linked with more than one root causes which requires more time to identify the factor(s). In this research, $Z_r(t)$ and welding speed are diagnosed as two factors which can cause weld defect. Both factors are usually controlled by the welders. Therefore, any instability of $\bar{h}(t)$ caused by the welders can be reflected immediately. Theoretically, the diagnosis process is easier and time saving as compared with the existing methods since only two factors are involved and more importantly, they are directly related to the root cause of weld defect.

In practice, the sequence of real-time monitoring and diagnosis of weld quality is presented in Fig. 4.2. The monitoring level is usually completed at step 2 but the diagnosis level is carried out at step 3. At step 1, voltage and current are measured simultaneously during the welding process. After both signals are sampled and digitized by the DAQ system, the $\bar{h}(t)$ is computed as a time recorded signature. At Step 2, the $\bar{h}(t)$ is checked instantly whether it is within the “Pass-Band”. Basically, weld defect is present if the $\bar{h}(t)$ is “out of band” and therefore step 3 is carried out immediately to diagnose the causes of weld defect. During the diagnosis process, the weld defect will be diagnosed by either factors based on the pre-defined criteria. Firstly, the weld defect due to abrupt change of $Z_r(t)$ will be checked. If the cause of weld defect is not diagnosed as

abrupt change of $Z_r(t)$, the wrong welding speed is identified. The welding speed is detected to be too fast when the $\bar{h}(t)$ is too low or vice versa. A real example of computation of $Z_r(t)$ and $\bar{h}(t)$ will be shown in the following section.

Figure 4.2 Sequence of monitoring and diagnosis process.

4.2 Computation of Time Record $\bar{h}(t)$ & $Z_r(t)$

In practice, several workpieces were prepared according to the Working Procedure Specification (WPS) given in Appendix D. They were used to perform FCAW manual 3G vertical welding job. The steel plate was AH 36, 25.4mm thickness. Fig. 4.3 demonstrates the dimensions of the workpiece. In order to completely join the 2 pieces together, it requires several numbers of welding passes to fill up the gap. According to the WPS, the minimum number of welding passes is 11. Therefore, the welder starts the first pass from the gap near to the ceramic backing and continues to weld on top of the previous pass. For vertical welding, the weld starts from point “A” and finishes at point

“B”. Weaving welding is necessary and the weaving width is depended on the width of weld area to be covered.

Figure 4.3 Dimensions of workpiece.

During the welding process, both voltage and current are sampled and recorded simultaneously according to the setup demonstrated in Chapter 3. Due to the sampling rate is relatively high, a huge amount of data points are generated even for a single welding pass. Therefore, the recorded data has to be saved into series of data files. Basically, about 33k of data points lasting for 11s welding time is saved into a data file. The time interval for each data point is 0.000333s based on the 3k Hz sampling rate. In order to demonstrate the experimental result, voltage and current signal from the first data file of 4th welding pass from a typical workpiece is plotted (see Fig. 4.4 and 4.5). After that, the recorded data is used to compute the corresponding $Z_r(t)$ and $Z_x(t)$ (see Fig. 4.6 and 4.7).

For digitized signals, the average heat being generated for a certain period of time is computed based on the number of data points, N :

$$\bar{h}(t) = \left(\frac{1}{N} \sum_{k=1}^N I_k^2 Z_{r,k} \right) \times \Delta T \tag{4.1}$$

This N has to be small enough so that the continuous time sequence of signature is reflected. We set the N to be 300 which make the ΔT to be 0.1s of welding time. In other words, we ensure that the welding voltage and current are strictly controlled throughout the welding process so that the variation of $\bar{h}(t)$ reflects the change of welding speed or $Z_r(t)$ only. In practice, a sensor should be used in order to measure the real-time welding speed. Fig. 4.8 shows that the computed $\bar{h}(t)$ is capable to reflect the time-varying behavior of heat input. In the followings, the correlation between the $\bar{h}(t)$ and its corresponding $Z_r(t)$ with the weld defect will be presented.

Figure 4.4 Example of welding voltage signal from a typical weld.

Figure 4.5 Example of welding current signal from a typical weld.

Figure 4.6 Corresponding $Z_r(t)$ of the typical weld.

Figure 4.7 Corresponding $Z_x(t)$ of the typical weld.

Figure 4.8 Average heat input per unit length of the typical weld.

4.3 Weld Defects Detection

In the followings, an example of comparison between Ultrasonic Test, $\bar{h}(t)$ and its corresponding $Z_r(t)$ with results of Macro Testing is presented in order to confirm the accuracy of the proposed method.

4.3.1 Weld Defects Detection by Ultrasonic Test

Ultrasonic Test was carried out on a typical workpieces. Basically, Ultrasonic Test was done firstly before the workpieces were destroyed during Macro Testing. Fig. 4.9 shows a typical Ultrasonic Test result for the workpiece. The plan view of Ultrasonic Test result is able to locate the weld defect and its length in size. On the other hand, the location of weld defect in depth, which is measured from top surface of workpiece is related to the n^{th} welding pass.

Figure 4.9 Typical result of Ultrasonic Test.

4.3.2 Weld Defects Detection by $\bar{h}(t)$ & $Z_r(t)$

In this case, an example of $\bar{h}(t)$ and $Z_r(t)$ from 4th welding pass of the same workpiece (as shown in Fig. 4.9) is presented in Fig. 4.10 and 4.11. It is observed that the sudden drop of $\bar{h}(t)$ and abrupt change of $Z_r(t)$ happen simultaneously at $t=29.8$ s. In order to correlate with the location of weld defect, the occurrence of such sudden change has to be converted into arc traveling distance. Basically, the arc traveling distance can be calculated by multiplying the measured welding speed with the recorded time. However, the actual welding speed was not measured during the tests. Therefore, only estimated welding speed at 1.28 mm/s of this welding pass is obtained based on the arc traveling distance divided by the total recorded time. After that, the weld defect is found at 38mm from the welding point “A”.

Figure 4.10 $\bar{h}(t)$ for 4th welding pass.

Figure 4.11 $Z_r(t)$ for 4th welding pass.

4.3.3 Weld Defects Detection by Macro Testing

Macro Testing is a destructive testing method which can physically identify the weld defects. Therefore, it is employed in this thesis to confirm the accuracy of Ultrasonic Test and the proposed method. Basically, every sample of Macro Testing has to undergo cutting, polishing and etching process in order to obtain the cross sectional view of the workpiece. Furthermore, the sample locations of the workpiece are also important so that they can be correlated with the result of Ultrasonic Test and $\bar{h}(t)$ correctly.

According to AWS D1.1 Standard, defect is found in the sample at 38mm from welding point “A” which slag inclusion is identified in between 2nd and 4th welding pass (see Fig. 4.12). This defect is categorized as “slag (0.8mm) at inter-pass fusion”. On the other hand, the sample at 230mm from welding point “A” also shows some defects but the locations of defects are different when correlating with the Ultrasonic Test result. As shown in Fig. 4.9, the detected defect should appear at 1st or 2nd welding pass. However, all the defects

shown in Fig. 4.13 appear at 3th, 4th and 6th welding pass. No defect is found at 1st and 2nd welding pass. Therefore, the Macro Testing results confirm that the monitoring result of $\bar{h}(t)$ is more accurate than Ultrasonic Test. On the other hand, the abrupt change of $Z_r(t)$ also indicates that the cause of weld defect is due to the unstable arc length. Although the cause of faulty weld can be due to fast welding speed, the $Z_r(t)$ will be diagnosed firstly and considered as the main factor in order to simplify the diagnosis process.

Figure 4.12 Macro Testing result at 38mm from welding point “A”.

Figure 4.13 Macro Testing result at 230mm from welding point “A”.

4.4 Identification of Pass-Band of $\bar{h}(t)$ by Taguchi Method

Design of Experiment (DOE) [77] is a series of tests which allow evaluating more than one factor at the same time. By varying those factors with a fixed combination, the effect of such factors on the response function is observed. In this case, the DOE method and sensitivity of experiment is used to identify the “Pass-Band” of $\bar{h}(t)$.

In this research, the Taguchi Method [78] was adopted as the DOE method. Basically, the number of factors, testing level and the response function has to be selected for the parameters of DOE. Table 4.1 describes that three factors (voltage, current and welding speed) are stimulated at two levels (high, low). The level of each factor and other relevant operating parameters are set based on the Working Procedure Specification given in Appendix D. The response function is the mean of $\bar{h}(t)$ which is computed according to the method mentioned in Chapter 3. Once the parameters of DOE are confirmed, a L8 array is constructed (see Table 4.2). Each run group of experiment is repeated for 5 times. When conducting the experiments, the $\bar{h}(t)$ is computed and shown in Table 4.3. After the experiments are done, a test on the adequateness of experiments has to be carried out to validate that the $\bar{h}(t)$ is linearly responsive within the range of factors. In this case, an additional run group is required and set at the middle point of all levels. The results shown in Table 4.4 confirm that the $\bar{h}(t)$ is adequate because the F_o is small as compared to the $F_{0.05, 1, 4}$ based on 95% confidence level. In the followings, the UCL and LCL can then be computed.

Table 4.1 Selected factors and testing levels.			
Factors	Level		Tolerance
	High	Low	
A: Voltage (V)	24	28	± 1
B: Current (A)	150	200	± 10
C: Welding Speed (mm/s)	4	7.5	-

Table 4.2 Setting of individual factors.			
Run	Factor Setting		
	Voltage (V)	Current (A)	Welding Speed (mm/s)
(1)	24	150	4
a	28	150	4
b	24	200	4
ab	28	200	4
c	24	150	7.5
ac	28	150	7.5
bc	24	200	7.5
abc	28	200	7.5
center	26	175	5.75

Table 4.3 Experimental results of $\bar{h}(t)$.					
Run	Mean Value of $\bar{h}(t)$ (J)				
(1)	352	341	341	346	341
a	433	421	418	414	417
b	448	437	452	460	440
ab	546	560	563	566	561
c	355	341	342	337	340
ac	405	424	419	415	417
bc	432	437	455	464	451
abc	560	556	558	555	559
center	439	446	455	446	441

Table 4.4 Computational results for validating the adequateness of $\bar{h}(t)$.	
Number of experiments at run group “center”, n_c	5
Number of experiments based on L8 array, N	40
Mean value of $\bar{h}(t)$ for n_c , Y_c	445
Mean value of $\bar{h}(t)$ for N , Y_N	442
Sum of square of curvature, $SS_{curvature} = \frac{N \times n_c}{N + n_c} (Y_N - Y_c)^2$	48.42
Mean square of error, $MS_E = \frac{\sum_i^{n_c} (y_i - Y_N)^2}{n_c - 1}$	49.68
$F_o = \frac{SS_{curvature}}{MS_E}$	0.97
$F_{\alpha, v1=level-1, v2=level(5-1)} = F_{0.05, 1, 4}$ (Appendix E)	7.71

The range of “Pass-Band”, bounded by the UCL and LCL is defined by the sensitivity of experiments. According to Philip [78], the sensitivity of experiments for L8 array is 1.17 standard deviation at 95% confidence level. Therefore, the UCL and LCL are found and shown in Table 4.5.

Table 4.5 Computational results for UCL and LCL.	
Standard deviation, $\sigma = \sqrt{\frac{\sum_{i=1}^N (y_i - Y_N)^2}{N - 1}}$	66.65
Upper Control Limit, $UCL = Y_N + 1.17 \times \sigma$	520
Lower Control Limit, $LCL = Y_N - 1.17 \times \sigma$	364

The obtained mean value, LCL and UCL are included in Fig. 4.10 and plotted again in Fig. 4.14 to illustrate the result of monitoring process. Basically, the weld defect is detected at $t=29.8s$ or 38mm from welding point “A” when the $\bar{h}(t)$ drops below LCL.

However, it is also observed that the $\bar{h}(t)$ frequently exceeds the LCL and therefore causes error during the monitoring process. This error is mainly because the welding speed was not measured during the welding process. In this case, the welding speed can be much slower during the tests and cause the $\bar{h}(t)$ to be higher than the expected results as shown in Table 4.3. Therefore, a welding speed sensor will be integrated into the monitoring and diagnosis system to measure the welding speed for future development so that the error can be eliminated.

Figure 4.14 $Z_r(t)$ for 4th welding pass with mean value and control limits.

4.5 Comparisons of Monitoring & Diagnosis Results

There are 20 samples of Macro Testing being cut from 5 workpieces and 12 of them were found to contain weld defects. The cutting locations of samples were decided by both Ultrasonic Test and $\bar{h}(t)$. Figure 4.15 shows the comparison between the results of Ultrasonic Test and $\bar{h}(t)$ based on the Macro Testing. Figure 4.15 is arranged in such a way that the results of Macro Testing reveal the weld defect physically and the results of

$\bar{h}(t)$ and $Z_r(t)$ from left hand size to right hand size. Finally, the results of Ultrasonic Test are presented for the comparison purpose. The “Yes/No” column is to show that the monitoring results agree with the result of Macro Testing.

Total 21 defects were identified and presented in Fig. 4.15. It reveals that most of the weld defects hidden in between welding pass are detected accurately by the $\bar{h}(t)$. Taking the Macro Testing as reference, the accuracy of $\bar{h}(t)$ is 95% against the Ultrasonic Test which is only 19%. Most of the Ultrasonic Test results are incorrect due to the wrong detection of depth or type of defect. The poor accuracy of Ultrasonic Test can be attributed to its limitations such as the size must be bigger than 2mm and the longitudinal side of defect has to be perpendicular to the direction of ultrasound wave transmission.

The high accuracy of quality monitoring by using $\bar{h}(t)$ is reasonable because the monitoring signature itself consists of the system property which is the resistance of impedance. The raw signals used for $\bar{h}(t)$ computation, voltage and current, are considered as sensing cum actuating signals which means that the measurement does not cause any loading error to the system. Therefore, the signals are measured without altering the system behavior. On the other hand, the resistance of welding is not possible to obtain due to the presence of reactance in the circuit. By measuring the $Z_{in}(t)$ of welding, they are separated completely into the real and imaginary part of $Z_{in}(t)$. Therefore, we are able to measure the resistance of welding which reflects accurately about the dynamic behavior of arc welding.

For the diagnosis of faulty weld, we have to confirm the threshold of $Z_r(t)$ as it is the first factor to diagnose. In this case, the $Z_r(t)$ for all the workpieces is observed in order to

select the threshold. Basically, the $Z_r(t)$ is seen from 0 to 0.3 Ohm for normal welding condition but it will increase sharply where weld defect is present (see Fig. 4.6 & 4.11). By definition, this “abrupt change of $Z_r(t)$ ” must have a high jerk in value. According to Fig. 4.15, 8 cases show that the $Z_r(t)$ is higher than 1 ohm which the defects are believed to be caused by unstable arc length. Based on this observation, the threshold of $Z_r(t)$ is fixed at 1 Ohm. Further fine tuning for this threshold is possible in future after more results are obtained and compared.

Defect No	Macro Testing			H/v (J/mm)	Diagnosis - 1	Diagnosis - 2	UT			Remark		
	Type of Defect	Location (mm)	Weld Pass	UCL - 520 LCL - 364	Abrupt Change of $Z_r(t)$	Yes/No	Type of Defect	Length (mm)	Depth (mm)	Yes/No	Sample No	Workpiece No
1	Slag at inter-pass fusion	38	4	319	15.13	Y	LOF	230 ~ 235	20 ~ 25	N	c7	T11
2	Slag at inter-pass fusion	100	3	312	0.75	Y				N	c8	
3	Accumulated porosity	192	3	201	58.5	Y				N	c9	
4	Slag at inter-pass fusion	192	4	566	6.1	Y				N	c9	
5	Accumulated porosity	230	6	336	0.41	Y				N	c10	
6	Slag at inter-pass fusion	230	3	266	1.06	Y				N	c10	
7	Slag at inter-pass fusion	230	4	354	6.1	Y				N	c10	
8	Slag at inter-pass fusion	142	4	272	0.46	Y				N	c12	T12
9	Slag at inter-pass fusion	142	5	277	0.48	Y				N	c12	
10	Slag at inter-pass fusion	204	3	323	0.36	Y				N	c13	
11	Slag at inter-pass fusion	204	4	174	17.1	Y				N	c13	
12	Slag at inter-pass fusion	204	8	293	0.6	Y				N	c13	
13	Slag at side wall fusion	40	4	150	19.8	Y	LOF	55 ~ 111	16 ~ 20	N	c14	T13
14	Accumulated slag at side wall fusion	100	2	277	0.65	Y	LOF	90 ~ 110	17 ~ 22	Y	c15	
15	Accumulated slag at side wall fusion	100	4	177	2.3	Y				Y	c15	
16	Accumulated slag at side wall fusion	100	6	368	0.46	N				Y	c15	
17	Accumulated slag at side wall fusion	185	2	324	0.47	Y				N	c16	
18	Accumulated slag at side wall fusion	185	4	285	0.53	Y				N	c16	
19	Slag at side wall fusion	125	5	628	0.3	Y	LOF	120 ~ 135	23 ~ 25	N	c19	G15
20	Slag at side wall fusion	210	6	640	0.22	Y	LOF	200 ~ 250	23 ~ 25	N	c20	
21	Slag at inter-pass fusion	200	3	296	0.47	Y	Slag Inclusion	52 ~ 82	14 ~ 17	Y	c26	G10
							Slag Inclusion	132 ~ 162	16 ~ 17			
							LOF	197 ~ 222	15 ~ 17			

Figure 4.15 Comparison of results for Macro Testing, $\bar{h}(t)$ and Ultrasonic Test.

4.6 **Prototype of Real-time Quality Monitoring & Diagnosis Apparatus for FCAW**

The results and discussions presented in this chapter confirm the capability of using $\bar{h}(t)$ and $Z_r(t)$ to perform real-time monitoring and diagnosis of weld quality. In the followings, a prototype of such apparatus has been developed for FCAW.

Fig. 4.16 shows the conceptual design of the apparatus. For signals acquisition, voltage and current probe are employed to measure the input signals. Basically, they are attached to the output port of the welding machine. With the voltage probe and current probe measuring the raw signals, they are acquired simultaneously by the DAQ system which is installed in an industrial computer. On the other hand, analog low pass filters are installed before the DAQ system to avoid anti-aliasing. Fig. 4.17 reveals the detail of each function to be done by the industrial computer and integrated system. The automated monitoring and diagnosis process is carried out by extracting the features of $\bar{h}(t)$ and $Z_r(t)$, and comparing with the UCL, LCL and threshold of $Z_r(t)$.

Figure 4.16 Schematic diagrams of the apparatus.

Figure 4.17 Signal processing and feature extraction.

Fig. 4.18 presents the overall view of prototype. It consists of a Central Control Unit (CCU), Remote Alarm Unit (RAU) and a pair of voltage probe and current probe. The industrial computer, DAQ system, signal processing board, relay I/O Card and DC power supply unit are included in the CCU to facilitate the signals acquisition and processing, computation, feature extraction, diagnosis and output the weld quality. Some of the components are shown in Fig. 4.19. On the other hand, the program algorithm and Graphical User Interface (GUI) are developed based on Labview™ 8.6, Full Professional Developer software and displayed on an 8” LCD monitor. Fig. 4.20 and 4.21 demonstrates the GUI display for the normal running condition and fault detected condition. Additionally, a RAU unit is designed as a hand held device with LED light and sound buzzer in order to alert the welder instantly when the weld defect is detected (see Fig. 4.22). Currently, an application of international patent filing is in-process to protect this newly invented technology.

Figure 4.18 Prototype of real-time quality monitoring and diagnosis apparatus.

Figure 4.19 Inner layout of CCU.

Figure 4.20 GUI display for normal running condition.

Figure 4.21 GUI display for fault detected condition.

Figure 4.22 Detail design of RAU unit.

CHAPTER 5

METAL TRANSFER DURING ARC WELDING

Metal transfer plays a major role in understanding the mechanism of arc welding. The $Z_{in}(t)$ -based weld quality monitoring and diagnosis system presented in the previous chapters serves an effective tool for studying the metal transfer phenomena of arc welding. This chapter will introduce the method and results. Section 5.1 introduces the set-up of an imaging acquiring system to catch the visible physical metal transfer. Section 5.2 focuses on the correlation between the time variation of $Z_r(t)$ and $Z_x(t)$ with the metal transfer phenomena. In Section 5.3, the capability of this method is further developed to provide a new classification method of metal transfer mode. Section 5.4 presents an investigation of different metal transfers and welding quality due to different shielding gases based on the newly developed method.

5.1 Monitoring of Metal Transfer

Fig. 5.1 shows the experimental set-up for the studying of metal transfers during arc welding. It includes the PHOTRON Fast Speed Camera used for the images recording. This camera was attached with the PTEMS Lens which the focus length of camera was kept at 355mm and the magnification of lens was set at 1.75. Due to the excessive light emitted from the welding arc, a costumed-made filter glass was attached to the lens in order to prevent the strong light from affecting the quality of images. On the other hand,

Unomat Super Spot Light was placed opposite to the lens so that it can create a back light source when the welding arc was traveling in between them. Therefore, clear images of metal transfer phenomena can be shot.

Figure 5.1 Experimental setup of image acquiring system.

Basically, the record images are two dimensional. Therefore, they are capable of reflecting the droplet transfer rate but only providing a rough gauge for the size of droplet. According to the literature review, the droplet transfer rate of metal transfer can go up to hundreds of droplets per sec (Hz) for Spray Transfer (ST) mode. In order to capture the rapid motion, the camera was set at 250 frames per sec with 1/23000 sec shuttle speed. The resolution of image was tuned to 1024x1024 pixels (1 Mega) so that the welding wire, droplet and weld pool are captured in the image. Fig. 5.2 demonstrates a typical image taken during the welding process. The brightest portion of image is the welding arc. On top of it, a droplet is in the process of being formed. It attaches to the welding wire because the attaching forces are still strong enough to hold it. Once the detaching forces overcome the attaching forces, the droplet detaches from the welding wire and drops to

the weld pool across the welding arc. In practice, the droplet transfer rate of a particular metal transfer mode can be measured easily by counting the numbers of frames involved in a complete cycle of droplet formation and detachment.

In arc welding, two typical shielding gases are used - Carbon Dioxide (CO_2) and Argon95%/CO₂5% (Ar95%). Testing for metal transfer mode was conducted in two sets of welding processes under different shielding gases. Table 5.1 shows the voltages and current settings for the welds. On the other hand, the tolerance of welding parameters is listed in Table 5.2. All the samples were done on 10mm thickness, AH36 steel plate according to the bead-on-plate test which has been discussed in Chapter 3.

The $Z_{in}(t)$ can be correlated with the real-time metal transfer if the acquisitions of $Z_{in}(t)$ and images were triggered simultaneously. However, it is not possible to record large amount of images due to the limited memory capacity of camera. In order to overcome this shortcoming, the camera was placed at the middle of weld bead so that it can start to record the images for total 1537 frames, or equivalent to 6.15sec of time recorded data

based on the specified frame rate. The placement of camera in corresponding with the acquired $Z_{in}(t)$ is illustrated in Fig. 5.3.

Table 5.1 Variation of welding voltage and current.		
Run No.	Voltage (V)	Current (A)
1	24	150
2	24	175
3	24	200
4	26	150
5	26	175
6	26	200
7	28	150
8	28	175
9	28	200

Table 5.2 Tolerance of welding parameters.		
Welding Parameters	Setting	Tolerance
Voltage (V)	-	±1
Current (A)	-	±10
Leading Angle (deg)	15	±1
Free Wire Length (mm)	15	±1
Wire Diameter (mm)	1.2	-
Welding Speed (mm/s)	4	-
Gas Flow Rate (l/min)	20	-

Figure 5.3 Placement of fast speed camera.

5.2 $Z_{in}(t)$ -Based Real-time Monitoring of Metal Transfer

Fig. 5.4 shows a sequence of images labeling from t_1 to t_{13} to demonstrate a typical cycle of the droplet formation and detachment for RUN 02 under CO₂ shielding gas. The time interval between 2 adjacent frames is 0.004sec (based on 250 frames per sec). At t_1 , the welding arc vanishes because the welding wire bridges the weld pool by the droplet which is formed earlier. After the droplet fully detaches from the welding wire, the welding arc between the welding wire and weld pool is reformed. On the other hand, severe weld spatter is observed from t_2 to t_4 because an impact force is created when the droplet drops on the weld pool. Due to the continuous melting of metal, another droplet starts to form at the tip of welding wire at t_5 . The droplet is pushed aside due to the unbalanced magnetic force and then sticks to the welding wire as a result of surface tension force which serves as the attaching force. At t_{13} , the welding wire bridges the weld pool again when the droplet drops to the weld pool. This metal transfer phenomenon is known as Short-circuiting Transfer (SCT) mode and the measured droplet transfer rate is equal to 19.23Hz based on 13 frame counts.

Figure 5.4 Sequence of images for a droplet formation and detachment cycle (SCT mode).

In order to correlate the $Z_{in}(t)$ with the metal transfer phenomenon, the corresponding time record $Z_r(t)$ and $Z_x(t)$ are shown in Fig. 5.5 and 5.6. Basically, ripple signals are found along the curves. They are oscillating at 300Hz which is caused by the input frequency of welding voltage and current. Along the welding time, the $Z_r(t)$ drops to near zero value at t_1 . After that, it starts to increase until t_5 and becomes relatively constant. At the end of the cycle, it experiences another sharp drop to zero again. For the $Z_x(t)$, it varies also along the welding time. From t_1 to t_5 , it turns from positive value to negative value and then increases continuously to positive value until t_{13} . Theoretically, the droplet transfer rate of metal transfer can be computed based on the period of cycle shown in time domain. For this particular cycle, the droplet transfer rate is estimated at 18.52Hz based on the period of time taken from t_1 to t_{13} ($1/(12.64-12.586)$). This result is approximately equal to the measured droplet transfer rate.

Figure 5.5 Corresponding time record result of $Z_r(t)$ (SCT mode).

Figure 5.6 Corresponding time record result of $Z_x(t)$ (SCT mode).

In the equivalent circuit, the welding arc is considered as an electric conductive gaseous column. Therefore, the formulation of R , L and C are employed to relate the 2 time record $Z_r(t)$ and $Z_x(t)$ with the specified metal transfer mode.

$$R = \rho \frac{\ell}{A} \tag{5.1}$$

$$L = \frac{V_L}{\frac{di}{dt}} \tag{5.2}$$

$$C = \frac{\epsilon_r \epsilon_0 A}{d} \tag{5.3}$$

where ρ is specific resistivity, ℓ is length, A is cross-sectional area, V_L is induced voltage, $\frac{di}{dt}$ is rate of change of welding current, ϵ_r is dielectric constant in between 2 plates, ϵ_0 is electric constant and d is gap distance for the welding arc. For the $Z_r(t)$, we assume that the ρ and A is constant. Therefore, the $Z_r(t)$ only varies proportionally to the

arc length (ℓ) of welding arc. As shown in Fig. 5.5, the $Z_r(t)$ drops to near zero value at t_1 because ℓ becomes zero due to the physical connection between welding wire and weld pool. When the welding arc is reformed, the $Z_r(t)$ increases from t_1 to t_5 as the ℓ increases. From t_5 until t_{12} , the $Z_r(t)$ is relatively constant because the droplet only attaches to the welding wire by attaching forces. Therefore, the ℓ does not change much. When the droplet grows big enough, it drops suddenly due to the strong gravity force. Eventually, it bridges the welding wire with weld pool at t_{13} when the $Z_r(t)$ reduces to zero.

The welding arc is a gaseous region which allows the L and C to form due to the self-inductance and capacitive-like behavior. Theoretically, the $Z_x(t)$ can be expressed as the subtraction of L with inverted C based on the Eq. 3.5 so that the change of $Z_x(t)$ is reflected by the formation of L and C . At t_1 , there is no welding arc due to the physical connection between the welding wire and weld pool. Therefore, C is equal to zero because no air gap is present. However, due to the self-inductance of welding arc when the welding current is flowing, L is computed. At this moment of time, the value of $Z_x(t)$ is maximum at 0.1. When the welding arc is reforming, it starts to behave like a capacitor. The $1/C$ can be seen as the ratio of distance between the welding wire and weld pool to the cross-sectional area of welding arc. In this case, it is same as the $Z_r(t)$ which is also proportional to the ratio of ℓ to A . During the reformation of welding arc, the increment of distance causes the $1/C$ to increase rapidly. Therefore, the value of $Z_x(t)$ jumps to minimum at -0.1. From t_5 to t_{12} , the $Z_x(t)$ increases gradually from negative regime to positive regime. The change of $Z_x(t)$ in this stage can be caused by two possible factors. Firstly, the $1/C$ does not change since the ℓ/A is relatively constant (as seen in Fig. 5.5). Therefore, the only possibility that causes the $Z_x(t)$ to increase is due to lesser welding

current variation which its degree of variation can be represented by the rate of change of welding current $(\frac{di}{dt})$.

Theoretically, higher $\frac{di}{dt}$ will experience larger variation. In order to confirm this result, the $\frac{di}{dt}$ is taken on the welding current which is filtered by applying a low pass digital filter at 50Hz. As illustrated in Fig. 5.7, $(\frac{di}{dt})_2$ is smaller than $(\frac{di}{dt})_1$ so that the L or $Z_x(t)$ continues to increase until the droplet detaches again.

Figure 5.7 Corresponding time record of welding current and its rate of change.

A typical Globular Transfer (GT) mode was observed from RUN 07 under CO₂ shielding gas (see Fig. 5.8). Similarly, the sequence of images labeling t_1 to t_{20} is presented to demonstrate the physical change of GT mode. At t_4 , the cycle starts when the droplet is detaching without bridging the welding wire with weld pool. Therefore, the welding arc does not vanish due to the physical connection between the welding wire and weld pool.

After that, another droplet grows at the tip of welding wire from t_5 to t_{17} due to the continuous melting of metal. Similar to SCT mode, the droplet is also pushed aside from the center of welding wire and stick to the tip of welding wire. It is observed that the droplet fully detaches from the welding wire at t_{20} which is confirmed by the existence of weld spatters from t_{18} to t_{20} . In this case, the images from t_4 to t_{20} describe the complete cycle and therefore the droplet transfer rate is measured at 14.7 Hz based on 17 frame counts.

The corresponding $Z_r(t)$ and $Z_x(t)$ are shown in Fig. 5.9 and 5.10. As compared with SCT mode, there is no welding arc reformation for GT mode because the droplet never bridges the welding wire with the weld pool and causes the welding arc to vanish. This phenomena is confirmed by the $Z_r(t)$ never reduces to zero value. On the other hand, the variation of $Z_x(t)$ for GT mode is also smaller which is measured from 0.05 to -0.05. Therefore, the L and C is expected to be smaller as compared to SCT mode. For the estimated droplet transfer rate, it is computed at 15.63 Hz ($1/(12.54-12.476)$) which is also close to the measured droplet transfer rate.

Figure 5.8 Sequence of images for a droplet formation and detachment (GT mode).

Figure 5.9 Corresponding time record result of $Z_r(t)$ (GT mode).

Figure 5.10 Corresponding time record result of $Z_x(t)$ (GT mode).

The presented results confirm the capability of the $Z_r(t)$ and $Z_x(t)$ in reflecting the physical change of metal transfer. After dividing the $Z_r(t)$ and $Z_x(t)$ curves into 3 stages, the metal transfer phenomenon can be characterized as (a) welding arc reformation; (b) droplet formation; (c) droplet detachment. As shown in Fig. 5.5 and 5.6, the Stage (a) only happens in SCT mode where the welding arc vanishes and then reforms after the

droplet detaches to the weld pool. During this period of time, the $Z_r(t)$ experiences a rapid increment but the $Z_x(t)$ reduces dramatically. At Stage (b), both SCT and GT mode takes a longer period time to complete and therefore causes slow droplet transfer rate. Due to stable welding arc is formed in this stage, the $Z_r(t)$ is relatively constant but the $Z_x(t)$ increases gently from negative regime to positive regime as a result of lesser variation of welding current. When the droplet grows big enough, the gravity force becomes large enough to cause the droplet detaching to the weld pool. Therefore, the droplet can either bridge the welding wire with welding pool under SCT mode or just simply detach under GT mode at Stage (c). In the followings, the features of $Z_{in}(t)$ are extracted and correlated with the metal transfer mode so that a new, real time classification method is introduced.

5.3 Classification of Metal Transfer Modes

As per discussed in Chapter 2, the classical metal transfer mode classification based on the welding voltage, current or wire feed rate is found to be inaccurate and less precise because all these parameters are not the welding system properties and therefore they are subjected to the changes due to the disturbances from environment. On the other hand, most of the existing methods used for real-time monitoring of metal transfer are either too expensive or complicated to be implemented for online production needs. Therefore, a real-time, accurate and easy-to-use classification method of metal transfer mode is proposed based on the $Z_{in}(t)$.

5.3.1 Feature of $Z_{in}(t)$

For the pattern recognition of metal transfer modes, the feature of $Z_{in}(t)$ has to be selected carefully. We often need to choose more than one features for pattern recognition. In

practice, the fewer features the better. In this case, we found that the location of $Z_r(t)$ close to zero is the only feature which is good enough to distinguish between SCT and GT mode (see Fig. 5.5). A threshold line of deciding whether it is close to zero is the recognition method of this particular feature. Based on the observation from the experimental results, this threshold line is set at 0.05 and the detail of pattern classification is shown in Table 5.3.

Table 5.3 Feature of $Z_r(t)$ for metal transfer mode classification.	
Metal Transfer Mode	Threshold Line of $Z_r(t)$ (Ω)
SCT	≤ 0.05
GT	> 0.05

In order to demonstrate the proposed method, an example of pattern recognition and classification implemented on the $Z_r(t)$ of RUN 04 under CO₂ shielding gas from 10.5 sec to 11 sec is presented in Fig. 5.11. Basically, a threshold line, T_1 is drawn at 0.05. The estimated result shows that there are 5 counts of SCT mode and 2 counts of GT mode according to the feature listed in Table 5.3. In the next session, the estimated results will be presented and compared with the measured one for the result validation.

5.3.2 Validation of $Z_{in}(t)$ –Based Classification Method

The validation is done for the welds under CO₂ shielding gas (see Fig. 5.12). In this case, a new classification method is proposed in order to distinguish between SCT and GT mode precisely. Basically, the estimated metal transfer modes are presented in terms of percent weightage over the total observation of a particular weld. Therefore, different metal transfer modes can be classified quantitatively.

Figure 5.11 Classification of metal transfer mode by using the proposed method.

In general, the estimated metal transfer mode agrees with the measured one which minor error less than 7% is reported (as shown in Fig. 5.12). This error can be mainly caused by the measuring mistake when we determine the mode from the images because the quality of images is inconsistent for some cases. On the other hand, the threshold line which is employed for the pattern recognition and classification can be inaccurate when the featured value of $Z_r(t)$ is too close to the threshold line. In order to improve the accuracy of experimental result, other type of pattern recognition and classification methods such as Artificial Neural Network, Fuzzy Logic and etc can be employed.

In modern welding technology, the optimization of welding process remains a challenge because no method is available to quantify the metal transfer mode precisely. In this report, the results mentioned above indicate that we are able to quantify the metal transfer modes by percent weightage. Therefore, the most desired combination of metal transfer modes can be achieved and then controlled throughout the welding process since the feedback can be on real-time basis if the monitoring process is automated by computerized system.

Figure 5.12 Results of metal transfer modes classification.

In conclusion, the capability of the proposed method was confirmed. For the monitoring of metal transfer, it can be used as a non-contact measuring tool to obtain the real-time and in-situ information. Furthermore, it also provides a better classification method of metal transfer mode which can reveal and quantify the type of modes in percent weightage. In the followings, a welding issue about the use of CO₂ and Ar95% shielding gas will be discussed in order to demonstrate the usefulness of the proposed method.

5.4 Quality Comparison of Arc Welding Using CO₂ and Ar95% Gas

Articles in literatures [79, 80] reported that the use of Argon gas can result into smaller size of droplet and faster droplet transfer rate. Therefore, the Spray Transfer (ST) mode is achieved. However, comprehensive reason has not been given to claim the advantages of using Argon gas due to the lack of understanding about the welding mechanism of arc

welding process. In this case, arc welding under two types of shielding gas, CO₂ and Ar95% gas are compared. We investigate the relationship between the physics of ST mode with the Fast Fourier Transform (FFT) analysis of $Z_r(t)$ and $Z_x(t)$. Finally, the comparison of average heat input per unit length for the two gases is made in order to find out the causes.

Fig.5.13 shows the sequence of images labeling from t_1 to t_9 for RUN 09 under Ar95% shielding gas. It is observed that a droplet forms and drops from t_1 to t_9 . This cycle is classified as GT mode based on the size of droplet and the slow droplet transfer rate measured at 27.8 Hz. During the detachment of first droplet, another droplet is found to form at t_8 and drops at t_9 . The size of this droplet is much smaller and it is not in spherical but longitudinal shape. In this case, the droplet transfer rate is measured at 125 Hz based on the 2 frame counts. Therefore, this cycle is classified as ST mode.

The corresponding time record result of $Z_r(t)$ and $Z_x(t)$ is shown in Fig. 5.14 and 5.15. However, it is more convenient to convert the time domain results into frequency domain because the frequencies shown in the frequency domain represent the periodic change of signal. Therefore, FFT analysis is applied on the corresponding $Z_r(t)$ and $Z_x(t)$. As shown in Fig. 5.16 and 5.17, the peak found at 110Hz proves the existence of ST mode due to the fast droplet transfer rate as indicated. On the other hand, the peak found at 25Hz also indicates the presence of GT mode for slow droplet transfer rate. Besides these two peak frequencies, other peaks at 100Hz, 200Hz and 300Hz are related to the power supply system because a 3-phase full wave control with 6 Silicon Control Rectifiers (SCR) is used to convert the 3-phase AC input to DC output.

Figure 5.13 Sequence of images for a droplet formation and detachment (ST mode).

Figure 5.14 Corresponding time record result of $Z_r(t)$.

Figure 5.15 Corresponding time record result of $Z_x(t)$.

Figure 5.16 Corresponding FFT result of $Z_r(t)$.

Figure 5.17 Corresponding FFT result of $Z_x(t)$.

Based on the FFT result shown in Fig. 5.17, we consider only the magnitude of $Z_x(t)$ below 50Hz in order to compare the magnitude of inductance (L) based on GT mode. It is observed that the $Z_x(t)$ under Ar95% gas is always lower as compared to CO₂ gas (see Fig. 5.18). This result implies that the magnitude of L is smaller under Ar95% gas. Since smaller L induces lower magnetic force, the droplet is not pushed aside from the center of welding wire. As a result, the droplet does not “stick” to the welding wire so that it can detach faster even though the droplet has not grown to bigger size. In other words, the ST mode can be obtained when the Ar95% gas is used.

Figure 5.18 Comparison of $Z_x(t)$ between CO₂ and Ar95% gas.

According to the Eq 3.11, the average heat input per unit length, $\bar{h}(t)$ is computed. If the $\bar{h}(t)$ is divided by the electrical input power, the efficiency of heat generation is obtained as

$$H_{eff} = \frac{\overline{h}(t)}{VI} \times 100\%$$

(5.4)

where VI is the electrical input power. In general, the H_{eff} for Ar95% gas is always higher than CO_2 gas (see Table 5.4). At low welding voltage, the difference of efficiency between CO_2 and Ar95% gas can go up to 7.4% (see Run No. 2). This is because less electrical input power is being conserved by the $Z_x(t)$ and therefore more input electrical power is converted into heat. With the higher H_{eff} , the welding wire can melt faster and cause the droplet to detach faster.

Table 5.4 Heat generation efficiency for CO_2 and Ar95% gas.		
Run No	Heat Generation Efficiency (H_{eff}) %	
	CO_2	Ar95%
1	94.30	98.08
2	90.63	97.98
3	93.14	97.41
4	96.35	98.60
5	95.57	98.64
6	93.93	98.83
7	97.49	98.60
8	97.78	98.51
9	98.03	99.27

With the experimental results shown above, a complete metal transfer mode classification based on the $Z_{in}(t)$ can be achieved. As shown in Table 5.5, the droplet transfer rate and disruption of welding arc serves as the two factors for the pattern recognition and classification. Basically, the droplet transfer rate can be directly related to the size of droplet which bigger droplet is always associated with slow droplet transfer rate and vice versa. Therefore, it clearly separates the ST mode from the SCT and GT mode.

Furthermore, the disruption of welding arc can also distinguish between the SCT mode and GT mode since it reflects the physic of metal transfer.

Table 5.5 New metal transfer modes classification based on the $Z_{in}(t)$.			
		Droplet Transfer Rate (Hz)	
		Low	High
Disruption of Welding Arc	Yes	SCT	
	No	GT	ST

For the practical use of the proposed classification method, both factors can be reflected easily by the $Z_{in}(t)$ following the monitoring method mentioned above. The established relationship between the $Z_{in}(t)$ with the welding parameters like welding voltage and current provides the easy guide for the welding parameters setting and adjustment. On the other hand, it is also capable to reveal the physics of metal transfer which has been confirmed and presented in the previous section. Consequently, a more comprehensive, useful and easy-to-use metal transfer classification method is invented.

CHAPTER 6

METALLURGY OF ARC WELDING

The established relationship between the $Z_{in}(t)$ and weightage of metal transfer modes provides a good platform to investigate the metallurgical change of weld conveniently if it is correlated with the metal transfer modes. In Section 6.1, Metallurgical Test at two levels was carried out in order to reveal the macro and micro structural change of weld. The macrostructure of weld allows the reinforcement angle of weld bead, weld penetration and width of heat affected zone (HAZ) to be measured. The microstructure of weld implies the metal transformation of weld metal and HAZ. In Section 6.2 and 6.3, the relationship between the macro and micro structural change of weld with the weightage of metal transfer modes will be evaluated in order to confirm the capability of $Z_{in}(t)$.

6.1 Metallurgical Test

Metallurgical Test was conducted at two levels in order to evaluate the welding metallurgy (see Fig. 6.1). The first is at macro level which the macro structural change of weld such as reinforcement angle of weld bead, weld penetration and width of HAZ were investigated. Theoretically, the macrostructure of weld mainly indicates the mechanical strength of weld.

The second is at micro level. This test involves the observation of metal transformation and micro structural change at the center of weld metal and the center of coarse grained HAZ by using optical microscope (see Fig. 6.2). According to the literatures, HAZ can be divided into three major sub-zones by grain structure: (1) Coarse grained zone; (2) Fine grained zone and (3) Transition zone. If the sub-zones of HAZ are distinguished according to the temperature distribution, coarse grained zone is considered as high temperature region and the others are low temperature region. The coarse grained zone is known as the most critical region as it reflects the major metallurgical change of weld due to the thermal cycle. The low temperature region is less important because only secondary effects like precipitation may occur. Therefore, the coarse grained zone of HAZ was evaluated. Based on careful selection of the samples from relevant categories of metal transfer mode which have been made in Chapter 5, the Metallurgical Test was carried out.

Figure 6.1 Metallurgical Test of arc welding.

Figure 6.2 Illustration of locations for Micro Testing.

Welding wire DW-50 (AWS A5.20/SFA-5.20) with diameter 1.2mm was used for the experiments. The chemical composition of the steel plate is listed in Table 6.1. For the sample preparation, total 8 samples of RUN 02, 03, 07 and 09 under CO₂ and Ar95% shielding gas were selected for the Metallurgical Test.

Table 6.1 Chemical composition of steel plate, Grade AH36.										
C	Si	Mn (min)	P	S	Cr	Mo	Ni	Cu	Cb	V
0.18	0.1/0.5	0.9/1.6	0.035	0.035	0.2	0.08	0.4	0.35	0.02/0.05	0.05/0.1

Fig. 6.3 demonstrates the cutting of a sample piece from the bead-on-plate test steel plate. The samples with 5mm width were cut at 40mm apart from the starting point of weld. They were then polished by different grades of grinding papers, dipped into 2% Nital agent and dried by air blower in order to obtain the cross sectional view of weld.

Figure 6.3 Sample cutting from the weld.

6.2 Correlation of Metal Transfer Modes with Macro Structural Change of Weld

In this report, Canon EOS550D camera with Tamron lens (AF 90mm F/2.8 Macro Dia. 55) was used to obtain the macrographs of weld. Under the Macro Mode setting of the camera, clear images were taken to show the macrographs of weld metal and HAZ together. In the followings, the measurement of the reinforcement angle of weld bead, weld penetration and width of HAZ were presented and the results were discussed.

6.2.1 Reinforcement Angle of Weld Bead

A typical example of measuring the reinforcement angle of weld bead, γ is shown in Fig. 6.4. Theoretically, the γ is measured from the top surface of sample to the tangential surface of weld bead near to its edge. Since it can be measured from either side of weld bead, the worst case is considered.

Figure 6.4 Measurement of reinforcement angle of weld bead, γ .

As shown in Fig. 6.5, the reinforcement angles of weld bead are compared from the highest weightage of SCT mode to the highest weightage of ST mode in order. It reveals that the reinforcement angle of weld bead for the weightage of SCT mode above 25% is always lower as compared to the other modes. Under SCT mode, the surface tension force is the dominating force to act on the molten metal at vertical direction when the welding wire bridges with the weld pool (see Fig. 6.6). This force is strong enough to restrict the weld pool oscillation which stimulates the molten metal to move sideways from the center of weld pool. Therefore, the width and height of weld bead is relatively narrow and high so that its reinforcement angle is small. For other type of metal transfer modes, the molten metal at the center of weld pool can move freely to the sideways due to the weld pool oscillation.

Figure 6.5 Reinforcement angles against metal transfer modes.

Figure 6.6 Surface tension force acting on the weld pool.

6.2.2 Weld Penetration

Fig. 6.7 demonstrates the measurement of weld penetration. In theory, a fusion line is defined as the boundary line to distinguish between the weld metal and HAZ (see Fig. 6.8). Therefore, the weld penetration is measured from the top surface of sample to the fusion line where the distance is the maximum.

Based on the results presented in Fig. 6.9, the weld penetration is affected by the weightage of metal transfer modes. In general, the molten metal under the effect of GT mode is able to penetrate more into the parent metal as compared to the other types of metal transfer mode. Furthermore, the effect of GT mode is significant even though its weightage is low.

The weak weld penetration of weld due to the 100% SCT or 95% ST mode is related to the gravity force caused by the impingement of droplets. Fig. 6.10 illustrates that the continuous detachment of droplets on the weld pool under GT or ST mode causes the impingement of droplets. When the droplets impinge on the weld pool, the gravity force

of droplets enhances the weld pool oscillation which delivers the molten metal from the top to the bottom of weld pool so that the molten metal can penetrate more into the parent metal. Therefore, the weld penetration under 100% SCT mode is bad due to the lack of gravity force. On the other hand, the gravity force of droplet is proportional to the size of droplet. Since the size of droplet under 95% ST mode is smaller than the GT mode, the weld penetration of weld is also bad as a result of the smaller gravity force.

Figure 6.9 Weld penetration against metal transfer modes.

Figure 6.10 Gravity force and impingement of droplets.

6.2.3 Width of HAZ

In practice, the boundary line between the HAZ and parent metal has to be determined so that the width of HAZ can be measured. However, it is difficult to identify this boundary line because the metal transformation in HAZ and the parent metal is a continuous process which takes place according to the temperature distribution. Fortunately, the difference of grain structure in the HAZ region causes different light reflection when it is viewed under optical equipment such as camera and optical microscope. As shown in Fig. 6.11, the region in lighter gray color is the HAZ and the parent metal is in darker color. Therefore, a boundary line between the HAZ and parent metal is drawn arbitrary according to the different color regions. In order to measure the width of HAZ, the largest distance measured from the fusion line to the HAZ boundary line is considered (see Fig. 6.12).

Figure 6.11 HAZ boundary line in between HAZ and parent metal.

Figure 6.12 Measurement of width of HAZ.

Fig. 6.13 shows that the width of HAZ is also affected by the weightage of metal transfer modes. The width of HAZ is relatively large when the weightage of SCT mode is below 45%. If we examine the heat transfer of weld, the small width of HAZ is actually caused by steeper temperature gradient and lower heat conduction at parent metal. As shown in Fig. 6.14, the temperature distribution along the radius of weld pool is presented. Theoretically, the heat conduction at parent metal depends on the temperature gradient along the radius of weld pool. When less heat is being brought to the bottom of weld pool due to the small gravity force, the temperature gradient becomes steeper. If the temperature gradient is steeper, the heat conduction in parent metal will be lesser. Therefore, less part of parent metal will transform into HAZ due to low temperature. On the other hand, the width of HAZ of 95% ST mode is also large even though the gravity force of droplet is weak under ST mode. It could be caused by the average heat input of ST mode which is naturally higher than the average heat input of SCT mode. Therefore, the peak temperature of weld is high because it is proportional to the average heat input. The higher peak temperature shifts the temperature distribution curve upwards so that it causes larger width of HAZ.

Figure 6.13 Width of HAZ against metal transfer modes.

Figure 6.14 Temperature distribution at weld pool and parent metal.

In general, the macro structural change of weld is affected by the weightage of the metal transfer modes. It reveals that knowing the weightage of metal transfer modes to the forming of a weld is important because it will affect the macrostructure of weld. For an example, 100% SCT mode or 95% ST mode limits the weld penetration but it can be improved significantly by mixing with GT mode. On the other hand, the width of HAZ can be reduced if the high weightage of SCT mode is involved. In other words, different weightage of metal transfer mode can help to improve a particular macrostructure of weld but deteriorate the other one. The findings presented in this thesis equip us with the knowledge to optimize the welding process by controlling the weightage of metal transfer modes so that the optimum macrostructure of weld can be achieved.

6.3 Correlation of Metal Transfer modes with Micro Structural Change of Weld

To evaluate the micro structural change of weld, optical microscope (ZEISS, Axioskop 2 MAT with ImagePro Plus) was used for taking the micrographs on the grain structure and microstructure of weld. The magnification of this microscope can be set up to 2000x which is capable enough to take clear images. In the followings, the grain structure and microstructure of weld metal will be evaluated firstly and followed by the HAZ.

Grain and microstructure of RUN 02, 07, 09 under CO₂ shielding gas and RUN 09 under Ar95% shielding gas were presented in order to reflect the effect of metal transfer modes based on 100% SCT mode, 90%, 100% GT mode and 95% ST mode. As shown in Fig. 6.15 to 6.18, the grain structure of these samples is found to be the same which is known as “Cellular Dendritic”. Theoretically, the solidification mode of these samples shall be the same because they have the same composition (solute content) and solidification

parameter throughout the experiments. In other words, the metal transfer modes have no effect on the grain structure of weld metal.

Figure 6.15 Grain structure of weld metal for RUN 02 under CO₂ shielding gas.

Figure 6.16 Grain structure of weld metal for RUN 07 under CO₂ shielding gas.

Figure 6.17 Grain structure of weld metal for RUN 09 under CO₂ shielding gas.

Figure 6.18 Grain structure of weld metal for RUN 09 under Ar95% shielding gas.

As shown in Fig. 6.19, several types of micro structure are revealed for RUN 02 under CO₂ shielding gas: (1) Grain boundary ferrite, PF (G); (2) Intragranular polygonal ferrite, PF (I); (3) Acicular ferrite, AF. They are commonly seen in the solidification of low alloy carbon steel after welding. When cooling the hot weld in the air, the microstructure of

weld metal forms according to the CCT diagram as per discussed in Chapter 2 (see Fig. 2.10).

Similar types of microstructure are also observed for RUN 07 and 09 under CO₂ shielding gas (see Fig. 6.20 and 6.21). However, both of them have larger volume fraction of PF (G) than RUN 02. It is caused by the cooling curves of CCT diagram for RUN 07 and 09 which are shifted towards the PF (G) regime due to the higher peak temperature of weld. Therefore, more PF (G) is formed. In order to confirm the difference of peak temperature, the average heat input of the samples is examined since the peak temperature of weld is proportional to the average heat input. As shown in Fig. 6.27, the average heat input of RUN 09 is the highest followed by the RUN 07 and 02. Therefore, the volume fraction of PF (G) for RUN 09 is also the highest.

Figure 6.19 Microstructure of weld metal for RUN 02 under CO₂ shielding gas.

Figure 6.20 Microstructure of weld metal for RUN 07 under CO₂ shielding gas.

Figure 6.21 Microstructure of weld metal for RUN 09 under CO₂ shielding gas.

For RUN 09 under Ar95% shielding gas, it is observed that no PF (G) but more AF is formed (see Fig. 6.22). This observation can be also validated by referring to the CCT diagram again. According to literatures, the regimes of micro structures in CCT diagram will shift to the right side if the content of Oxygen is reduced. Since the shielding gas is

95% Argon gas with only 5% CO₂, it is believed that the content of Oxygen due to decomposition of CO₂ gas is also low. Having the similar cooling curve of RUN 09 under CO₂ shielding gas based on the close average heat input, the PF (G) is unable to form as its regime of formation has been shifted further away from the cooling curve.

Figure 6.22 Microstructure at weld metal for RUN 09 under Ar95% shielding gas.

To evaluate the grain and microstructure of HAZ, the same samples, RUN 02, 07 and 09 under CO₂ shielding gas and RUN 09 under Ar95% shielding gas were presented. As shown in Fig 6.23 to 6.26, micro structure like: (1) Ferrite with Aligned Second Phase, FS (A); (2) Ferrite Carbide with Pearlite, FC; (3) Bainite, B; (4) Martensite, M, are observed with similar volume fraction throughout the samples. In other words, there is no difference shown in the microstructure of HAZ due to the weightage of metal transfer modes. On the other hand, similar result is also obtained for the grain structure of HAZ because it is hardly to identify the difference in volume fraction.

From literatures, the transformation of metal at HAZ is depended on the peak temperature and residence time. Basically, the residence time is referred to the exposure time of heating and cooling under a thermal cycle. On the other hand, the peak temperature at HAZ is defined as the melting temperature of metal at fusion line. Since the material of all the samples is the same, they should experience the same thermal cycle with same peak temperature. As a result, the grain and microstructure of HAZ is found to be the same regardless the weightage of metal transfer modes.

Figure 6.23 Grain and microstructure of HAZ for RUN 02 under CO₂ gas.

Figure 6.24 Grain and microstructure of HAZ for RUN 07 under CO₂ gas.

Figure 6.25 Grain and microstructure of HAZ for RUN 09 under CO₂ gas.

Figure 6.26 Grain and microstructure of HAZ for RUN 09 under Ar95% gas.

Figure 6.27 Average heat input per unit length against metal transfer modes.

In conclusion, the weightage of metal transfer modes has no effect on the micro structural change of weld metal and HAZ. Theoretically, the content of Oxygen, peak temperature of weld and residence time are the key factors which affect the grain and microstructure of weld. It is found that the metal transfer modes or the $Z_{in}(t)$ is inherently unable to reflect the content of Oxygen. On the other hand, the peak temperature and residence

time cannot be correlated with the weightage of metal transfer modes since they are decided by the material properties and cooling process. As a result, the weightage of metal transfer mode is unable to reflect the micro structural change of weld.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes and concludes the works and findings of this research and also provides the direction for possible future research and development work. Section 7.1 concludes that the proposed method is capable to perform real-time weld quality monitoring and diagnosis for FCAW with promising accuracy. Basically, compared to the conventional resistance employed widely in literatures, $Z_r(t)$ is much more accurate because it is obtained without the interference of inductive noise. The method also enhances the monitoring and classification method for metal transfer mode in real-time. This capability helps to further investigate the metallurgical change of weld. Section 7.2 suggests two possible research directions. One is to improve the design of welding machine and the welding process in order to deal with the arc blow problem. The other one is related to the development of a numerical model for the simulation of arc welding.

7.1 Summaries and Conclusions

Heavy industries count on fusion welding to join structural parts. The integrity of the resulted structures is thus much affected by the quality of welding. For current state of art technology, there are many available methods for monitoring and diagnosis of the weld quality which can be mainly categorized into two classes: destructive and non-destructive testing. Most of them however cannot deliver satisfactory results for weld quality

assurance because they sacrifice the productivity, accuracy, cost effectiveness, efficiency or robustness. Therefore, the development of a real-time, in-situ and non-destructive quality monitoring method is crucial for retaining both high productivity and good quality.

7.1.1 Quality Monitoring and Diagnosis of Arc Welding

In this research, an innovative real-time quality monitoring and diagnosis method was developed by employing the average heat input per unit length, $\bar{h}(t)$ and resistance (real part of impedance), $Z_r(t)$ as the monitoring signatures. Basically, these signatures are obtained easily by measuring the welding voltage and current simultaneously. The measurement is done at the output terminal of welding machine and therefore does not jeopardize the welding job. On the other hand, the proposed method is real-time, in-situ, robust and low cost because the voltage probe, current probe, DAQ and signal processing system are inexpensive and their sizes are compact.

In chapter 3, the dependency of $Z_{in}(t)$ upon five important operating parameters: welding voltage, current, welding speed, free wire length and leading angle of welding torch was evaluated. The standard deviation of both $Z_r(t)$ and $Z_x(t)$ are close in value and they are influenced by the mentioned operating parameters. Basically, the standard deviation of $Z_r(t)$ is directly related to the stability of welding arc. Higher standard deviation of $Z_r(t)$ indicates unstable welding arc. To avoid unstable welding arc, higher voltage and faster welding speed are desired because they keep the standard deviation at low level while current, free wire length and leading angle should be lowered down.

The mean of $Z_x(t)$ is always equal to zero due to energy exchange between $L(t)$ and $C(t)$. On the other hand, the mean of $Z_r(t)$ is only affected by the voltage, current and free wire

length according to the Ohms' Law. While the voltage or free wire length is increasing, the mean of $Z_r(t)$ increase accordingly. Conversely, the mean of $Z_r(t)$ decreases when the current is increasing. In practice, these findings can help to optimize the welding process only when other factors such as metallurgical change of weld is considered concurrently.

The heat input per unit length is known well as an important factor for arc welding. However, it is incorrect to assume that the heat being generated and consumed for welding is equal to the input electrical power as often rendered in literature. From the measurement of $Z_{in}(t)$, it is obvious that the equivalent circuit of welding process does not only consist of resistor but also inductor and capacitor. The difference between the $Z_r(t)$ and conventional resistance obtained from Ohm's Law confirms this suggestion. Therefore, in our method the $\bar{h}(t)$ is proposed. As compared with the conventional heat input per unit length, the experimental results of $\bar{h}(t)$ is always lower because some of the input electrical power is conserved in $Z_x(t)$. In addition, the difference of heat input per unit length is larger when current is increasing but it becomes smaller when voltage is increasing. This finding shows that the energy being conserved in the $Z_x(t)$ is proportional to current but inversely proportional to voltage.

A method for real-time monitoring and diagnosis of weld quality was then developed. Basically, the $\bar{h}(t)$ is monitored in real-time to assure the weld quality during the welding process. The weld is said to be faulty once the $\bar{h}(t)$ is out of a "Pass-Band". This "Pass-Band" is pre-defined by the Upper Control Limit (UCL) and Lower Control Limit (LCL) which are determined by using Taguchi Method. Taking Macro Testing as reference, the accuracy of proposed method is excellent which can achieve 95% accuracy. On the other hand, the same procedure reveals that the accuracy of Ultrasonic Test is only 19%. The

relatively low accuracy of Ultrasonic Test can be attributed to its requirements such as the defect size being bigger than 2mm in length; the longitudinal side of defect has to be perpendicular to the direction of ultrasound wave transmission, and etc.

Based on the monitoring and diagnosis strategy presented in Chapter 4, faulty welds can be further diagnosed in order to find out the major causes. Basically, two major causes of faults are diagnosed in sequence:

- (1) Abrupt change of $Z_r(t)$ (arc length);
- (2) Welding speed too fast or slow.

In fact, these causes are related to the welding skill being developed by the welder. Therefore, proper skills such as changing the free wire length and welding speed accordingly are trained so that weld defect can be minimized.

As the proposed method is real-time, accurate, easy-to-use, low cost and robust, a real-time monitoring and diagnosis apparatus was developed to evaluate the skill performance of trainee welder. The simple system could be easily modified to ensure the weld quality for FCAW.

7.1.2 Monitoring and Classification of Metal Transfer Mode

The capability of $Z_{in}(t)$ is further extended to perform in-situ monitoring of metal transfer which are directly related to the quality of arc welding. As per discussed in Chapter 5, the two time record of $Z_r(t)$ and $Z_x(t)$ are employed to describe the physics of metal transfer. By referring to the formation of resistance, inductance and capacitance, the cycle of droplet formation and detachment can be correlated with the variation of the two time record data. Furthermore, these time records are divided into 3 stages in order to

characterize the metal transfer phenomenon: (a) welding arc reformation; (b) droplet formation; (c) droplet detachment. It reveals that the welding arc is always unsteady and disrupted periodically under SCT mode at Stage (a). At Stage (b), bigger size of droplet always forms under GT mode but much smaller size of droplet forms under ST mode. Basically, the droplet detaches and drops to the weld pool during Stage (c) when the detaching forces overcome the attaching forces. With these new pieces of information, a new classification method of metal transfer is proposed.

The welding current and voltage based methods cited in literatures for the metal transfer classification are inaccurate or less precise because these signatures do not represent the characteristics of welding system as impedance does. Based on the selected features of $Z_{in}(t)$, the metal transfer modes can be classified and then presented in terms of percent weightage over the total observation of a particular weld. In other words, the weightage of metal transfer is quantified in real-time so that we are able to control the desired metal transfer mode and optimize the welding process.

7.1.3 Correlation with the Metallurgical Change of Weld

With the established relationship between the $Z_{in}(t)$ and weightage of metal transfer modes, it can further correlate with the metallurgical change of weld. Basically, the metallurgical change of weld is revealed at macro and microstructure. As per discussed in Chapter 6, the macro structural change of weld is correlated with the weightage of metal transfer modes. By evaluating the relationship between the reinforcement angle of weld bead, weld penetration and width of HAZ with the weightage of metal transfer modes, it is found that the SCT mode has negative influence on the reinforcement angle of weld bead. On the other hand, the GT mode promotes deep weld penetration as compared to

the SCT and ST mode. However, the GT and ST mode are not desirable to produce a thin width of HAZ. In other words, different weightage of metal transfer modes has mixed effect on the macro structural change of weld and therefore the weld quality. Further investigation of the results is essential so that the weld quality can be improved by controlling the weightage of metal transfer modes.

For the micro structural change of weld, it is found that the solidification of weld metal or grain growth of HAZ only depends on the content of Oxygen, peak temperature of weld and residence time. Based on the experimental results, the weightage of metal transfer modes cannot be correlated with the change of the content of Oxygen, peak temperature and residence time. Therefore, the weightage of metal transfer modes is not suitable for reflecting the micro structural change of weld. However, the $Z_r(t)$ may provide a possibility to investigate the relationship with the peak temperature since it is used to compute the average heat input per unit length.

7.2 Future Direction and Development Work

Two possible research directions are proposed. The first one makes use of the weightage of metal transfer modes and its close relationship with the macro structural change of weld to improve the performance of welding machine. On the other hand, a numerical model based on the transduction matrix is proposed so that the welding mechanism is investigated based on the electrical input and thermal output simultaneously. It provides a new room of studying the welding mechanism which is closer to the nature of welding process. In the followings, the concept will be presented for each of the proposals.

7.2.1 Reduction of Magnetic Force Acting on Welding Arc

As shown in Chapter 3, the $Z_x(t)$ takes away a portion of input power which does not contribute to the heat generation. Conversely, magnetic force is induced by the $Z_x(t)$ and it causes “arc blow” problem. This magnetic force tends to deflect the welding arc so that the droplet can be deviated from its traveling path. Therefore, severe weld defects such as lack of fusion and excessive weld spatter are resulted.

As reported by Sindo [3], a permanent magnet is used to assist the weld pool oscillation so that the depth of weld penetration can be increased (see Fig. 7.1). The idea of this method is to manipulate the magnetic field in the weld pool so that more molten metal can be moved to the bottom by the induced magnetic force. Inspired by this method, the same idea can be used to eliminate the magnetic field in the welding arc. In practice, the magnetic field in the welding arc should be eliminated by placing the permanent magnet at the proper location. The final weld quality will be evaluated by the weightage of metal transfer modes and the macro structure of weld. Eventually, the most suitable design of the permanent magnet and its position can be achieved.

Figure 7.1 Schematic diagram of weld pool stirring by a permanent magnet [3].

7.2.2 Numerical Modeling of Arc Welding

According to Ling *et al* [79 - 81], 2 ports, 4 poles model has been employed to construct a transduction matrix which is capable to model an electro-mechanical system such as piezo electric transducer, bimorph impedance transducer and electric DC motor. They revealed that the relationship between the input voltage and current with output force or torque and velocity can be modeled as 4 transduction functions. Each of the transduction function is viewed as a frequency response function for one input variable and one output variable. They also proved that the newly formed 2x2 transduction matrix is capable to not only monitor the health condition of an electro-mechanical system but also measure the output of the system such as force and velocity.

The same concept of using such transduction matrix for system modeling can be applied on the arc welding since it works exactly like an electro-thermal system which converts the electrical power into the heat. Fig. 7.2 and 7.3 presents the possible way to model the arc welding. Basically, one of the requirements to construct the transduction matrix is to identify the physical input and output port. As shown in Fig. 7.2, the input port refers to the DC electrical power which connects V_1 to welding wire and V_2 to the parent metal where the voltage drop across the parent metal is negligible. Therefore, the welding current is able to flow through the welding wire, droplet and welding arc. For the output port, Nemchinsky [82] suggested that we should focus on the interface between the droplet-welding arc and droplet-welding wire where the major heat transfer phenomena take place. Therefore, the heat loss through convection and radiation to the air and weld pool is assumed to be small and steady as compared to the heat transfer taking place at the mentioned interfaces. In order to determine the heat flow in droplet, T_1 is considered as the temperature at the interface between droplet and welding arc. T_2 is indeed the

melting temperature of welding wire at the interface between droplet and welding wire.

By assuming the constructed model is linear, no energy generation and consumption, the relationship between the input and output port can be expressed as

$$\begin{bmatrix} V \\ I \end{bmatrix} = \begin{bmatrix} \bar{T}_{11} & \bar{T}_{12} \\ \bar{T}_{21} & \bar{T}_{22} \end{bmatrix} \times \begin{bmatrix} T \\ Q \end{bmatrix} = [\bar{T}] \times \begin{bmatrix} T \\ Q \end{bmatrix} \tag{7.1}$$

Where $[\bar{T}]$ is the transduction matrix of arc welding and $\bar{T}_y$ is the frequency response function elements. $\bar{T}_{11}$ and $\bar{T}_{21}$ are the transduction functions of input voltage and current to the output temperature. On the other hand, $\bar{T}_{12}$ and $\bar{T}_{22}$ are the transduction functions of input voltage and current to the output heat flow. Since these four functions are the system properties of arc welding, they can accurately characterize the dynamic change of energy conversion and heat transfer of arc welding. The developed transduction matrix is very useful as it can be employed to study the heat flow problem of arc welding which has not been covered under this thesis.

Figure 7.2 Schematic diagram of FCAW welding showing the locations of 4 poles.

Figure 7.3 Corresponding 2 ports, 4 poles model of a typical consumable arc welding.

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APPENDIX

APPENDIX A

APPENDIX B

Assembly of Steel Table

Robot Controller & Automatic
Welding Triggering System

X-Y Cartesian
Robot

Actual Experimental Setup

Torch Holder &
Welding Torch
Assembly

APPENDIX C

Runs	Mean Value of Conventional Heat Input (J)					Mean Value of $\bar{h}(t)$ (J)				
	411	404	394	397	389	352	341	341	346	341
(1)	448	437	435	431	434	433	421	418	414	417
a	540	534	547	539	536	448	437	452	460	440
b	586	584	583	582	578	546	560	563	566	561
ab	371	366	368	367	360	355	341	342	337	340
c	414	433	429	418	429	405	424	419	415	417
ac	485	480	506	509	503	432	437	455	464	451
bc	568	566	570	564	574	560	556	558	555	559
abc	474	471	477	467	466	439	446	455	446	441
center										

APPENDIX D

Y12

JURONG SHIPYARD LTD.

WELDING PROCEDURE SPECIFICATION

WPS : EQ56/PLEH-FC-02
PQR : EQ56/PLEH-FC-02-02
DATE : 01 APR 2002

WELDING PROCESS : FCAW
MANUAL / AUTO : SEMI-AUTO
WELDING PROGRESS : VERTICAL (UPHILL)
WELDING POSITION : 3G

CODE : AWS D1.1(2000)
CLIENT SPEC
WPS: FCAW-S040-01
PQR: S8-FCFC-AAANX-040

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JOINT PREPARATION AND WELDING SEQUENCE (UNIT IN MM)

DIMENSION OF TEST PIECE : 25.4 x (200 + 200) x 600 NO. OF PASSES : 11

BASE METAL :
SPECIFICATION : ABS
MATERIAL CLASS : EQ56 TO EH36

QUALIFICATION RANGE
THICKNESS : 3.2 mm ~ UNLIMITED
PIPE DIA : N.A.
LINE-UP CLAMP : N.A.

CLEANING : WIRE BRUSHING / GRINDING
STRINGER BEAD : YES
WEAVE BEAD : YES, MAX 13mm
BACK GOUGE : YES

PASS NO.	ELECTRODE NAME	CLASS	GROUP	DIA	AMPS	VOLTS	DC/AC	POL	SPEED MM/MIN
1	KISWEL K-71UT	E71T-9J	F6	1.2 mm	140~170	22~26	DC	EP	100~150
2~8				1.2 mm	150~180	24~28	DC	EP	250~450
9~11				1.2 mm	170~200	24~28	DC	EP	250~450

Note : PREHEAT TEMP : T 38 mm ~ 65 mm 65°C
T OVER 65 mm 110°C

HEAT TREATMENT
PREHEAT TEMP : REMOVE MOISTURE ONLY
PREHEAT TYPE : HEATING TORCH
INTERPASS TEMP : 300 °C Max
PWHT TEMP : —
HOLD TIME : —

GAS
SHIELD GAS : CO₂
GAS COMP : 100%
FLOW RATE : 14~20 L/MIN
BACK GAS : N.A
PURGE RATE : N.A

QA/QC SECTION
DATE : 16/04/2004
SIGN :
6 MAY 04
Approved by:

Joe Gouder

APPENDIX E

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TABLE D-6 F Values

		$F_{.10; \nu_1, \nu_2}$ 90% confidence [†]									
		Degrees of freedom for the numerator (ν_1)									
		1	2	3	4	5	6	7	8	9	10
Degrees of freedom for the denominator (ν_2)	1	39.9	49.5	53.6	55.8	57.2	58.2	58.9	59.4	59.9	60.2
	2	8.53	9.00	9.16	9.24	9.29	9.33	9.35	9.37	9.38	9.39
	3	5.54	5.46	5.39	5.34	5.31	5.28	5.27	5.25	5.24	5.23
	4	4.54	4.32	4.19	4.11	4.05	4.01	3.98	3.95	3.94	3.92
	5	4.06	3.78	3.62	3.52	3.45	3.40	3.37	3.34	3.32	3.30
	6	3.78	3.46	3.29	3.18	3.11	3.05	3.01	2.98	2.96	2.94
	7	3.59	3.26	3.07	2.96	2.88	2.83	2.78	2.75	2.72	2.70
	8	3.46	3.11	2.92	2.81	2.73	2.67	2.62	2.59	2.56	2.54
	9	3.36	3.01	2.81	2.69	2.61	2.55	2.51	2.47	2.44	2.42
	10	3.28	2.92	2.73	2.61	2.52	2.46	2.41	2.38	2.35	2.32
	11	3.23	2.86	2.66	2.54	2.45	2.39	2.34	2.30	2.27	2.25
	12	3.18	2.81	2.61	2.48	2.39	2.33	2.28	2.24	2.21	2.19
	13	3.14	2.76	2.56	2.43	2.35	2.28	2.23	2.20	2.16	2.14
	14	3.10	2.73	2.52	2.39	2.31	2.24	2.19	2.15	2.12	2.10
	15	3.07	2.70	2.49	2.36	2.27	2.21	2.16	2.12	2.09	2.06
	16	3.05	2.67	2.46	2.33	2.24	2.18	2.13	2.09	2.06	2.03
	17	3.03	2.64	2.44	2.31	2.22	2.15	2.10	2.06	2.03	2.00
	18	3.01	2.62	2.42	2.29	2.20	2.13	2.08	2.04	2.00	1.98
	19	2.99	2.61	2.40	2.27	2.18	2.11	2.06	2.02	1.98	1.96
	20	2.97	2.59	2.38	2.25	2.16	2.09	2.04	2.00	1.96	1.94
Degrees of freedom for the denominator (ν_2)	22	2.95	2.56	2.35	2.22	2.13	2.06	2.01	1.97	1.93	1.90
	24	2.93	2.54	2.33	2.19	2.10	2.04	1.98	1.94	1.91	1.88
	26	2.91	2.52	2.31	2.17	2.08	2.01	1.96	1.92	1.88	1.86
	28	2.89	2.50	2.29	2.16	2.06	2.00	1.94	1.90	1.87	1.84
	30	2.88	2.49	2.28	2.14	2.05	1.98	1.93	1.88	1.85	1.82
	40	2.84	2.44	2.23	2.09	2.00	1.93	1.87	1.83	1.79	1.76
	50	2.81	2.41	2.20	2.06	1.97	1.90	1.84	1.80	1.76	1.73
	60	2.79	2.39	2.18	2.04	1.95	1.87	1.82	1.77	1.74	1.71
	80	2.77	2.37	2.15	2.02	1.92	1.85	1.79	1.75	1.71	1.68
	100	2.76	2.36	2.14	2.00	1.91	1.83	1.78	1.73	1.70	1.66
	200	2.73	2.33	2.11	1.97	1.88	1.80	1.75	1.70	1.66	1.63
	500	2.72	2.31	2.10	1.96	1.86	1.79	1.73	1.68	1.64	1.61
	∞	2.71	2.30	2.08	1.94	1.85	1.77	1.72	1.67	1.63	1.60
		$F_{.05; \nu_1, \nu_2}$ 95% confidence [†]									
		Degrees of freedom for the numerator (ν_1)									
		1	2	3	4	5	6	7	8	9	10
Degrees of freedom for the denominator (ν_2)	1	161	200	216	225	230	234	237	239	241	242
	2	18.5	19.0	19.2	19.2	19.3	19.3	19.4	19.4	19.4	19.4
	3	10.1	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79
	4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96
	5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74
	6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06
	7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64
	8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35
	9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14
	10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98
	11	4.84	2.98	3.50	3.36	3.20	3.01	2.95	2.90	2.85	2.82