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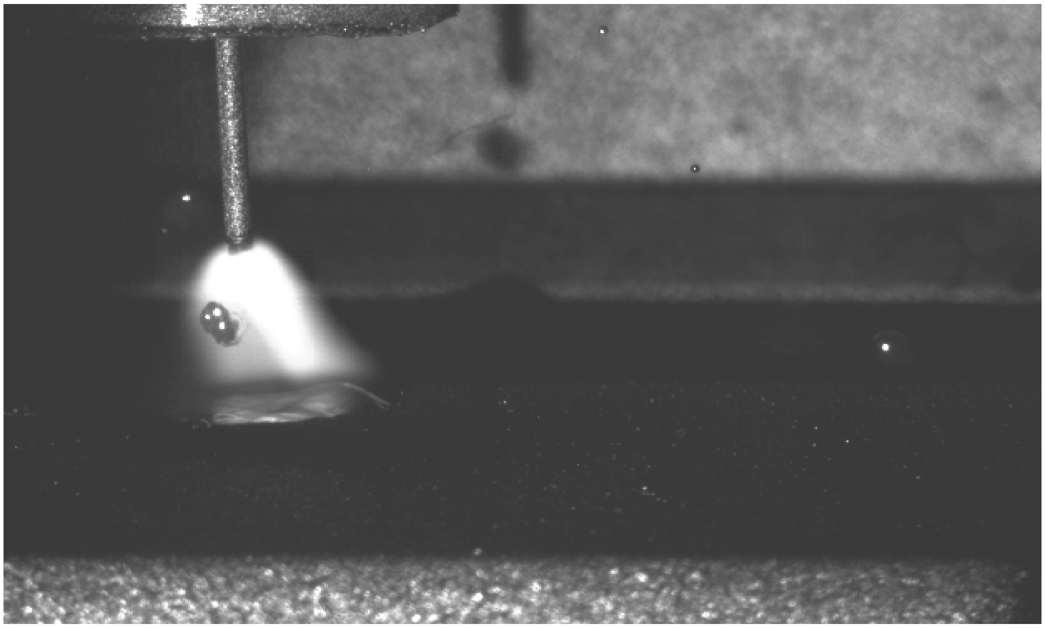

Evaluation of Wires and Testing Methodology for MAG Welding

Master of Science Thesis

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Göteborg, Sweden, 2012

Evaluation of Wires and Testing Methodology for MAG Welding

by

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Cover:
High Speed Camera sample image of Wire #2 during welding test.
Illustrations in Thesis Section 3.1

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Development of Testing Methodology for MAG wires
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Abstract

In this project a methodology for testing MAG wires was conducted. The method involves the use of some advanced technologies like a high speed camera and a high frequency data logging devise to capture the welding starting properties, in which six wires both copper and bare were selected for the tests, while setting most parameters such as work piece material, power source, voltage, current and wire feed speed as constants. The main purpose is to evaluate the High Speed Camera usage as a non-real-time sensor for the suggested method. At the mean time a comparison was established between the selected wires, entailing their coating, type of arc used, welder's opinions on performance, integrity of solidified weld among others.

This project was divided into 3 tasks, the first task was recording welding tests using the high speed camera, the second task involved testing the wires manually with experienced welders to compare their subjective opinion to the data collected from the first task, and finally the third task was a comparison of the filet weld size of the same six wires, thus reflecting weld integrity.

Using the method of high speed camera and data logger shed some light on several features and introduced fresh new aspects that were not possible to attain otherwise such as the time to establish a stable arc for each wire and its dependence on wire cuts and type of arc used, while comparisons between wires showed how wire composition, coating type and arc applied affect welding starting properties and voltage/current trends. It was concluded that the unstable arc duration is prolonged in case of the presence of wire-cuts or solidified droplets on wire tips and that copper-coated wires have fewer spatter and non-spherical shaped droplets compared to bare wires. Finally, it was also proven that weld bead integrity and flatness increases with increasing applied voltage.

Keywords: MIG/MAG, welding, High Speed Camera, arc starting properties, fillet weld, effective throat

Organization

This thesis is organized into 7 chapters as follows:

Chapter 1

An introduction concerning the project motivation and aim.

Chapter 2

A theoretical background of some papers and researches; it contains important definitions of some processes and parameters used in the project.

Chapter 3

A description of the project's three tasks and their experimental procedures.

Chapter 4

Contains the results of all of the three tasks.

Chapter 5

Discussion of the results.

Chapter 6

Is a final conclusion of the whole project.

Chapter 7

Suggestions for future investigations.

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Contents

Abstract III

Organization V

Acknowledgments VII

Contents IX

Chapter 1 Introduction 1

1.1 Motivation 2

1.2 Aim of the Project 2

Chapter 2 Background 5

2.1 MIG/MAG Welding Process 5

2.2 Shielding Gas 8

2.3 Arc types 8

2.3.1 Short Arc 9

2.3.2 Globular Arc 10

2.3.3 Spray Arc 10

2.4 Arc Stability and Start Properties Abstract 11

2.5 Wire Chemistry 13

2.6 Spatter 16

2.7 Stick-out 16

2.8 Weld shape 17

2.9 Sensors in the field of welding 20

Chapter 3 Experimental Procedures 23

3.1 Task #1 High Speed Camera Welding Tests 24

3.2 Task #2 Manual Welding Tests 27
3.3 Task #3 Fillet Weld Size Measurements 30
Chapter 4 Results 31
4.1 Task #1 Results - High Speed Camera Welding Tests 31
4.1.1 Short Arc 34
4.1.2 Spray Arc 36
4.2 Task #2 Results - Manual Welding Tests 38
4.2.1 Short Arc 38
4.2.2 Globular Arc 39
4.2.3 Spray Arc 39
4.3 Task #3 Results - Fillet Weld Size Measurements 40
4.3.1 Short Arc 41
4.3.2 Globular Arc 42
4.3.3 Spray Arc 43
Chapter 5 Discussion 45
5.1 Task #1 Discussion - High Speed Camera Welding Tests 45
5.2 Task #2 Discussion - Manual Welding Tests 48
5.3 Task #3 Discussion - Fillet Weld Size Measurements 49
5.4 Summary 40
Chapter 6 Conclusion 53
Chapter 7 Suggestions for Future Studies 57
References 59
ESAB Welding Evaluation Form 63

Chapter 1
Introduction

Evidence of several joining techniques was documented as early as in the Bronze Age, there was always a need to create or repair metal structures by joining the pieces of metals through various fusion processes using heat in almost all cases. Welding is one of the vital processes that helped in the industrial revolution and until our time, welding is still the backbone of many industries. Metal Inert Gas / Metal Active Gas (MIG / MAG) or sometimes called Gas Metal Arc Welding (GMAW) is one of the frequently used welding processes accounting for over two-thirds of welding production in developed countries [1]. The process includes many types of equipment where the welding wires and the power sources are both important in terms of the possibility of future improvements. In this project the development of testing methodology of MIG/MAG wires was studied. Tackling issues like arc stability, droplet transfer, integrity of welding process, weld geometry and penetration. In general, the methods of monitoring welding processes are usually based on the measurements of several physical quantities and their analyses, in this project; welding current intensity and welding voltage their mutual relation with time in particular and the high speed camera recording occurrences in the arc was the monitoring method, other measurements (not included in the project) comprise noise emitted, arc light and acoustic emission from a material. Here, this method was used along with a continuation of manually testing the wires and finally measuring the weld output fillet size.

1.1 Motivation

MIG/MAG is used extensively in key industries, for instance in ship building, pipeline, transportation, offshore, maintenance and repair heavy machinery and many other fields. All requires a steady rate to improve the whole process, judging by the effect MIG/MAG had on industry since its invention, one understands how important it is in our world. Setting a methodology for testing MIG/MAG wires will add more knowledge and will help develop the whole welding process giving the customer a better choice to pick the best wire according to the desired application.

1.2 Project Aim

The project's aim is to establish a methodology for testing MAG wires and verify if the suggested method provide more information comparing to other available methods, while tackling the strengths and weaknesses of different types of commercially available wires from an array of different manufacturers for further studies.

The method suggests the use of an Ultra High Speed Camera to detect occurrences during welding such as the wire starting properties and the time it took to achieve a stable arc. The task was directed towards analyzing this particular initial part, with the help of a high frequency data acquisition system (data logger) to analyze the incoming voltage/current data. Two other test types were included in the study, a subjective evaluation of the selected wires' performance by experienced welders and study of the weld shape and profile, later the two test results were compared for consistency.

Short and Spray arcs were used in the first task while Short, Globular and Spray Arcs were used on the other two tasks. Six wires were selected in this project, two manufactured by ESAB AB and the rest from three other manufactures. Among the six wires; four bare (uncoated) wires and two copper-coated wires. The project is divided in three tasks explained in detail in Chapter 3.

Chapter 2
Background

This chapter deals with defining some processes and parameters used in this project, in addition to the literature review done throughout the project duration. Starting by defining the welding technology used in the project, the different types of electric arcs. After that introducing shielding gas used, chemistry of wires, tools and equipment used in the different tasks and finally a review on fillet weld shape.

2.1 MIG/MAG Welding Process

The basic idea behind MIG/MAG welding is that a metallic wire is fed through the welding gun and melted in an arc. The wire acts as both the current carrying electrode and the weld metal filler wire. Electrical energy for the arc is supplied by a welding power source, which is the device that ignites the electric arc and maintains steady voltage and current throughout the welding process. Power sources have many features of their own, to name a few; voltages, currents, wire feed speeds and arc lengths among many others can be adjusted and controlled [2]. The arc and the pool of molten material are protected by a shielding gas, which is either inert or active, in which comes the name MIG (Metal Inert Gas), MAG (Metal Active Gas) and sometimes called a general name GMAW (Gas Metal Arc Welding).

The following briefly illustrates how the MIG/MAG process works:

The arc (1) - strikes between the work-piece and wire (2)
The wire is both the electrode and the filler material.
Wire is fed from a reel or drum (3), into drive rollers (4), which push the wire through a flexible conduit (5) in the hose package (6) to the gun (7).

Electrical energy for the arc is supplied from a welding power source (8), to the hose package (6) and to the contact tip (9) in the welding gun, where it is transferred to the electrode (2) (wire). **Shielding gas** (10), protects the electrode (2), the arc (1) and the weld pool (12) from the surrounding air, flows through the gas nozzle (11) that surrounds the contact tip.

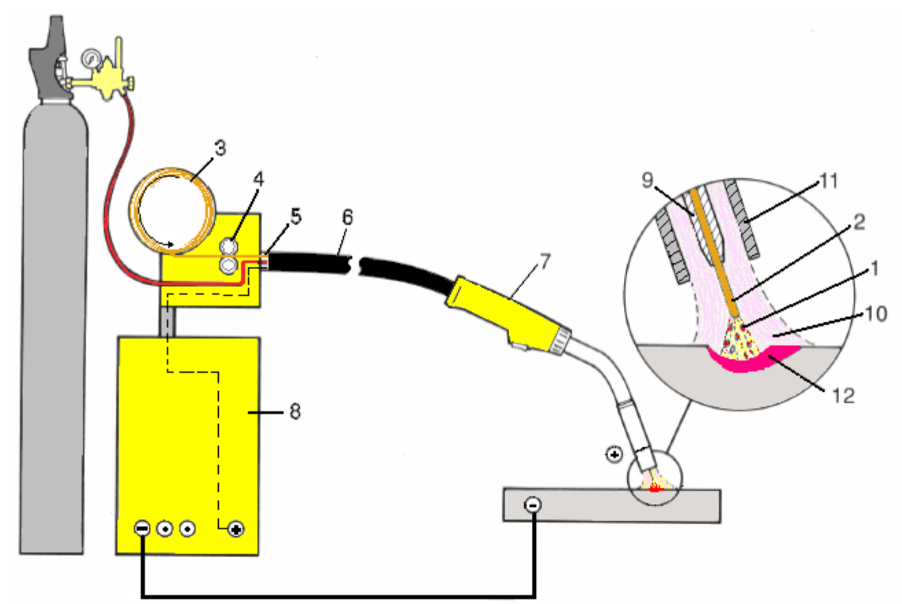

Figure 2.1 Illustration of MIG/MAG welding tools - Courtesy of ESAB AB

1. Electric arc.
2. Electrode.
3. Reel or drum.
4. Drive rollers.
5. Flexible conduit.
6. Hose package.
7. Welding gun.
8. Power source.
9. Contact tube.
10. Shielding gas.
11. Shielding gas nozzle.
12. Weld pool.

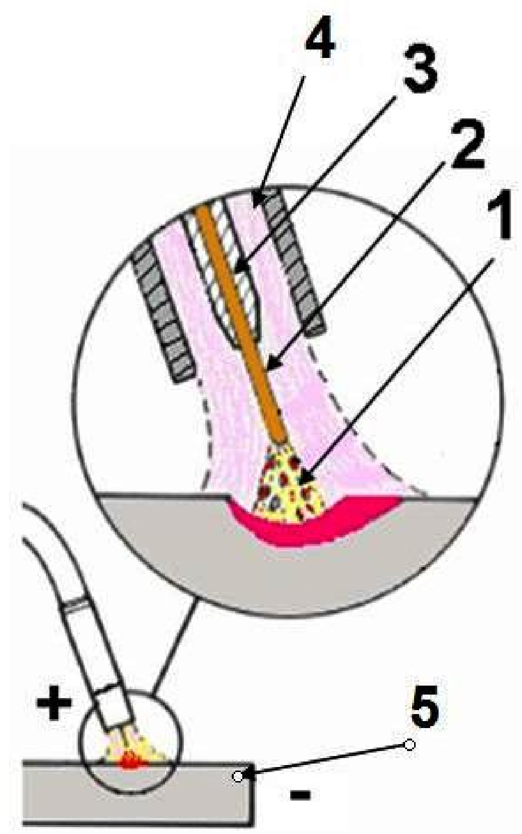

Figure 2.2 Arc creation in MIG/MAG - Courtesy of ESAB AB

The Arc itself is created as Figure 2.2 illustrates:

- The wire (2) is in contact with the work-piece (5) whereby an arc (1) is created due to difference in potential.
- The arc (1) melts the material to be welded
- Gas (4) shields/protects the weld area and the wire from the surrounding air. In MAG it also influences the weld.
- The wire (2) is continually fed forward, keeping the arc alive and producing the weld pool.
- Electrical energy for the arc is supplied to the contact tip (3), in the welding gun, which in turn transfers it to the wire (2). [3]

MIG and MAG are particularly popular among other welding methods for their:

- High productivity
- High flexibility
- Wide range of plate thicknesses (from 0.5 mm and upwards)
- Low heat input helps avoid deformation and distortion of thin plates
- Welds all commonly encountered structural materials, such as mild, low-alloy and stainless steel, aluminium and its alloys, and several other non-ferrous metals
- Welds in almost all welding positions
- Ease of automation makes it applicable to both large-scale industries and smaller workshops

On the other hand MIG/MAG still have some limitations, for instance in outdoors applications, as the shielding gas must be protected from draughts and the inaccessibility of some weld locations due to the rather large welding gun.

2.2 Shielding Gas

The choice of shielding gas is one of the primary factors that MIG/MAG productivity and quality highly depends on. Improving and choosing a suitable shielding gas is needed to establish a stable arc, obtain smooth metal transfer, good weld shape, achieve appropriate penetration and to reduce fume emissions. Hence, it is of extreme importance to select the correct shielding gas for each application. All tasks in this project used CORGON18 gas as it is largely available and commonly used, composed of Aragon 82% and Carbon dioxide 18%, hence throughout the project welding tests will be called MAG welding tests. Aragon gas is used for its inertness preventing the oxidation of the vulnerable weld pool. According to I. Pires [4] it was verified that the necessary voltage to obtain a stable metal transfer increase as the Carbon dioxide content of the mixture increases. This indicates that the arc stability decreases with the increases of carbon dioxide content in the mixture. This is due to the fact of the high thermal conductivity of Carbon dioxide, which gives rise to more heat loses by conduction and thus the necessity to use higher voltages for the same current intensity to initiate and stabilize the arc.

2.3 Arc Types

There exists four major arc types/metal transfer modes, Short, Globular (or mixed), Spray and Pulsed Arc. Only the first three types of Arcs are covered in this project.

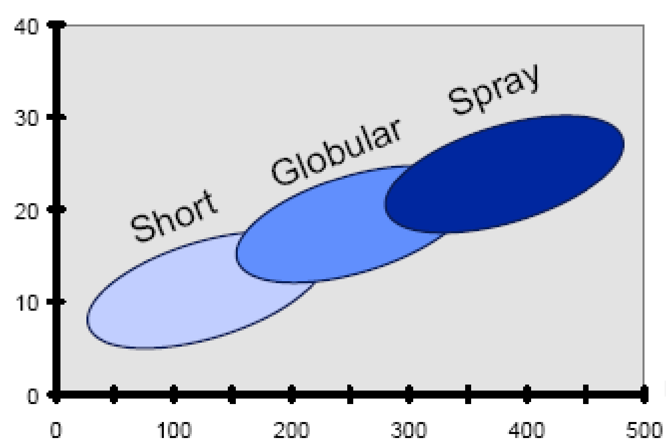

Figure 2.3 Voltage vs. Current and possible arc types

Figure 2.3 illustrates how the type of arc depends on the applied voltage (Y-axis) and the current intensity (X-axis).

As a common rule in welding, high voltage/current results in larger arc and accordingly larger weld pool i.e. base material and wire rapidly melts, and would need faster wire feed speed to compensate for the weld pool and vice versa.

2.3.1 Short Arc

Considered the most common form of MIG/MAG welding arc, recognized by its ability to weld thin and thick plates fast in all positions using relatively low voltages and currents with lower deposition rates than Globular and Spray arcs. It has a low to moderate heat input compared to other types of arcs, producing a small weld pool that freezes quickly. One of its fundamental features is that it produces relatively large droplets of molten metal that momentarily short-circuit the arc. The short circuits affect the stability of the arc and create welding spatter, which may cause after-work to clean up the work piece.

Figure 2.4 shows how a Short Arc cycle is formed:

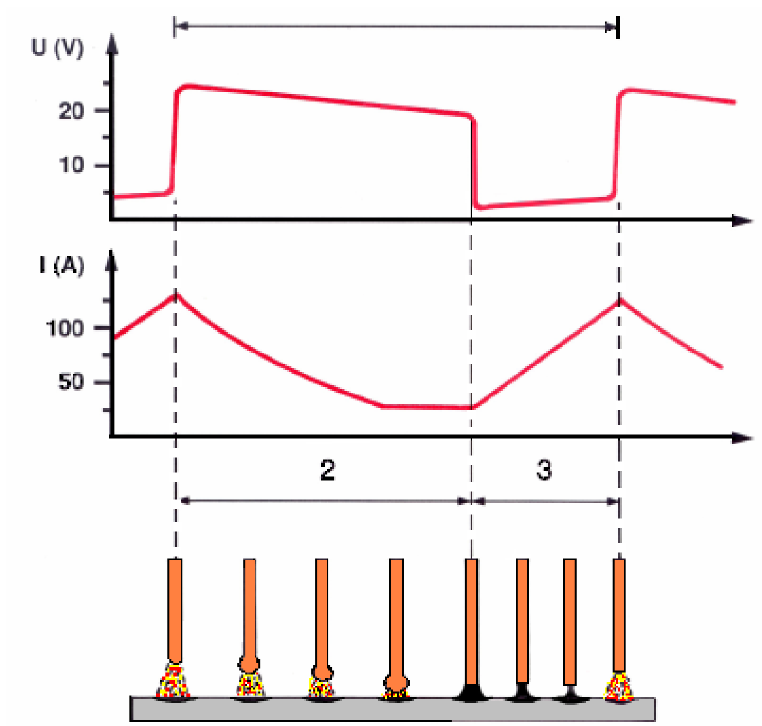

Figure 2.4 Short arc cycle

1. A drop of molten metal forms and grows on the end of the electrode
2. When the drop is so large that it contacts the weld pool, the arc is short-circuited, which causes a rise in current producing spatter and a drop in voltage

3. Until the drop is detached, the arc will be formed again melting the wire. A new drop will start to form. The current will decrease and the arc voltage will increase until another short-circuit occurs.

2.3.2 Globular Arc

Increasing the short arc welding current and arc voltage moves the arc into the Globular (or mixed) arc operating range, regarded as a state of transfer between short arc and spray arc metal transfer. Globular arc easily operates on Carbon dioxide as shielding gas instead of the more expensive Aragon gas with considerably high deposition rates [5], although it is characterized by the following features:

- The molten metal droplets vary in size & are a mixture of short-circuiting and non-short-circuiting droplets.
- Result in an unstable arc
- Produces large quantities of spatter and fumes
- The least desirable arc type
- Can be achieved with all sizes of electrodes [6]

2.3.3 Spray Arc

Increasing the Globular arc welding current and voltage moves the arc into the spray arc operating range. Spray arc is also commonly used; it sprays a stream of tiny molten droplets across the arc, from the electrode wire to the base metal. Spray arc transfer uses relatively high voltage, current and wire feed speed values, compared to short and globular arcs.

Advantages of spray arc transfer:

- High deposition reaching a rate of 60 mm/sec [5]
- Large, easily flowing weld pool
- Good fusion and penetration
- Good bead appearance

- Capability of using larger diameter wires
- Presence of very little spatter
- Automated productivity

Limitations of spray arc transfer:

- Used only on material 3 mm and thicker
- Limited to flat and horizontal fillet weld position, except for some spray transfer on aluminum.

2.4 Arc Stability and Start Properties

Nowadays, the wire manufacturing technology is quite widespread globally among producers. Nearly all of the available MIG/MAG wires on the market are similar to an extent, giving similar behavior in the weld output. Generally, there exist two unstable arcs in any welding process, one at the start and one at the end. Experience within ESAB AB claims that wires differ in the duration of the ignition arc. The initial part of the welding process, the weld unstable part or the ignition time, is the part that welding tests were concerned about in this study. For each test in Task #1, the welding process was recorded in graphs and images and the unstable arc duration was measured.

A stable welding process is a property of the welding arc; an ideal welding arc is characterized by:

- Uniform material transfer
- Constant arc length
- No spatter
- Minimum noise

- Stable weld pool
- Good penetration
- If short-circuit transfer was used, the arc burning time (1) and the short-circuit time (2) should be uniform as shown in Figure 2.5

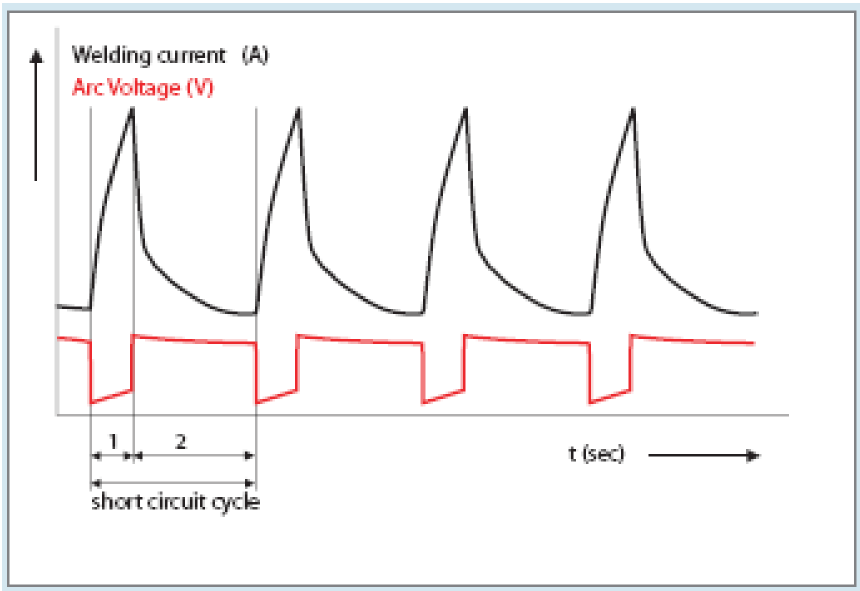

Figure 2.5 Ideal Short Arc cycle - (1) Arc burning time (2) Short-circuit time

- If spray transfer was used, time between the transfer of two subsequent drops should always be the same

Although there are a number of parameters that could be altered to affect the duration of the unstable arc, in this project it was decided to keep everything constant except for the wires used and the type of arc applied.

M.Suban [7] mentioned that the usual technique used to assess the stability of a welding process is by controlling and analyzing the results obtained from measurements. The least complicated method used is the analysis of the dependence of welding current and welding voltage on time. When an arc starts voltage begins with a very high value lagged by current in order to sustain arc ignition. The values of both keep on fluctuating until a stable arc i.e. with minimal fluctuations is established. The stable arc has much lower voltage and amperage than during ignition. The duration of this unstable initial part can produce lots of unfavorable noise and spatter if it takes a long time. As it is discussed later in the project, the variations in voltage and current occur very fast and are influenced by a variety of factors such as:

- Arc's electric and thermal conductivity that would alter the voltage and current used and in turn change the rate of material deposition
- Arc length; consequently voltage, current and wire feed speed would change
- Type of shielding gas used, as mentioned in section 2.2.

2.5 Wire Chemistry

The surface chemistry of wires is an another essential factor in determining the arc stability and the integrity of the weld itself whether wires coated with a layer of copper (copper-coated) or wires with no copper coating (bare wires), as the ease of wire feeding is directly related to arc creation and its stability later on. Certainly the exact wire chemical composition and surface coating is unknown due to trade secrets but there are a number of elements that are usually present in the wire composition essentially due to compatibility issues between the wire and the base metal. In principal wire and base material should be as chemically compatible as possible, since the wire melts with the base metal to form a composition of both, incompatible wires would lead to poor welds prone to cracking and corrosion.

Table 2.1 gives a typical range for these elements.

	Element	wt% range
1	Carbon (C)	0.01 - 0.10
2	Silicon (Si)	0.30 - 1.00
3	Manganese (Mn)	0.70 - 2.0
4	Phosphorous (P)	0.001 - 0.03
5	Sulphur (S)	0.001 - 0.03
6	Copper (Cu)*	0.01 - 0.50

*In case of copper coated wires

Table 2.1 Typical MIG/MAG wires chemical composition

That is in addition to a balanced amount of Iron (Fe) and some inevitable impurities. Other wires might include Titanium (Ti) and Oxygen (O). The contents of these elements have to be precisely controlled during wire manufacturing as they make up the wire chemical composition prior to coating. They also contribute to the surface tension of the melted wire droplets during welding; a large value of surface tension would lead to large droplets of spatter [10].

Although Copper-coated wires are desirable for their electrical conductivity and electrical resistance, they have two main drawbacks. The first is having a reputation in which the copper coating layer de-scales while feeding after long hours of usage. The reason behind this is a fact called the bridge phenomenon, where during the wire copper coating process, the precipitation rate of the copper coating layer is faster in protruded edges than in dented portions of the wire surface. The result is that all protruded edges are connected together like a bridge leaving an uncoated area in-between at the bottom. Later on while feeding, these bridges are broken off in the form of scales/dust that accumulates at the welding tip, giving rise to an unstable arc owing to fluctuations in wire feed [9].

Although droplet formation, size and transfer frequency regardless of the wire coating depends on surface tension, electromagnetic forces, gravity and arc drag force [8] wire coating type also has an added effect. As the second problem encountered with copper-coated wires is that droplets released are smaller than that attained by a wire having no copper plating. Moreover, the droplets are not in spherical form but rather ellipsoid elongated toward the dropping direction, causing an instantaneous short circuit. Later these droplets cause spatter as they are broken into smaller particles and scattered, a reason why bare wires are also used. Bearing in mind that the optimum droplet shape is small sized spherical droplets (arising minimum or no spatter on collision) regularly and smoothly transferred to the base metal [10].

Huwang and others [9] suggested that adding alkali and alkaline earth metals on the wire surface improves the adhesiveness of the copper coating on the wire giving excellent feedability and arc stability during welding. Such elements as Sodium (Na), as it is easily ionized by the welding current, resulting in an increase in droplet transfer with reduced spatter. Alkaline earth metals such as Calcium (Ca), which has a low ionization energy that improves arc stability, increases the short circuit frequency of the arc during welding and reduces spatter. It also precipitates between Copper and Iron grains which increases the fineness and compactness of the plating layer. Magnesium (Mg), being highly reactive contributing to de-oxidation of the molten weld and arc stability.

In addition, another paper suggested the use of Alkali metal compounds as plating without the use of Copper in coating, which is just bare wire with alkali coating. Such Alkali metals as Potassium (K) and Cesium (Cs) can be used as arc stabilizers preventing short circuiting [10].

Furthermore, according to some welders, chemical impurities present within the wire or the base metal composition might produce slag formations. Slag formations are islands of impurities that float on top of weld pools and can easily be removed after the weld solidifies. Usually having large islands of slag indicates that the melted wire penetrated deep into the base metal.

2.6 Spatter

Spatters are produced during welding, as explained earlier in this chapter it is one of the major results of poor arc stability. Spatter occurs while welding with each and every short circuiting, as the wire touches the weld pool giving mini-explosions during which the current reaches a maximum value and voltage a minimum value, as explained in section 2.4. Spatters are drops of molten metal which are not a part of the weld but solidify at the weld surface. Moreover, it produces a significant loss of material and gives the weld a much poorer appearance. Spatters are a problem not only for the quality of the weld, but they also influence the welding equipment negatively, spatters tend to adhere on the welding nozzle, which in turn reduced the flow of shielding gas resulting in a turbulent flow. Cleaning of the welding nozzle is thus required during welding operation, which additionally extends the production time.

2.7 Stick-out

Is the contact tip-to-work distance and is controlled by the welder by changing the position of the welding gun relative to the work piece, as shown in Figure 2.6. It influences the welding processes, as increasing stick-out distance increases the electric resistance and the wire will be excessively heated. Also it influences the welding current and voltage resulting in changed rate of deposit, penetration and arc stability. As a general rule, longer stick-out gives less current, higher voltage and decreases heat input.

The distance shall therefore be kept constant while welding, as otherwise it can result in current variations, spatter and altering heat input to the weld. All stick-out distances were constant in this project according to the type of arc used.

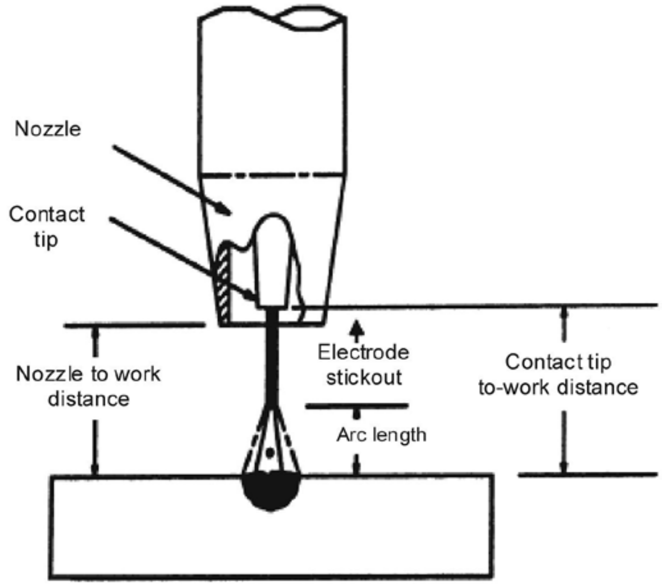

Figure 2.6 Illustration of Stick-out distance . [24]

2.8 Weld shape

In this study all experiments of Tasks 2 and 3 were based on fillet welds (a weld joining two edges at right angles), primarily for their predominance, popularity and being straight forward to inspect. Fillet weld shape geometry is very important in determining the strength and integrity of the weld. Two factors contribute to that; size and profile. First, weld size is based on a term called weld throat, which equals 0.707 times the leg length or the fillet weld size, as shown in Figure 2.7. Weld throat = 0.707xLeg length.

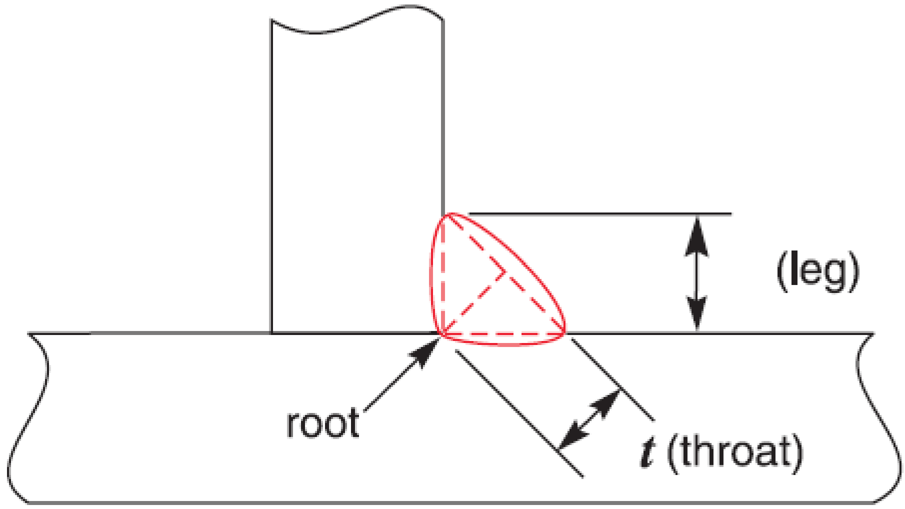

Figure 2.7 Illustration of fillet weld measurements

Fillet weld size or leg length is the side of the largest triangle inscribed inside the fillet weld, usually a right angle triangle [12].

A supplement evolved to the “weld throat formula” as mentioned in a Welding Innovation Journal [11], in which the root penetration is taken into consideration i.e. depth of penetration beyond the root. Effective throat is the weld throat plus the root as shown in Figure 2.8. In this way a strong fillet weld can be achieved with reduced leg length but with increased root, giving better appearance and less material utilization. But taking into consideration that the variables affecting penetration, like welding position, current, voltage, wire feed speed, travel speed, preheat, welding procedures etc. More importantly the metallurgical issues, since MIG/MAG uses a consumable electrode, its components melts and combine with the parent metal, compounds containing elements such as carbon, copper, sulfur, phosphorous can enter into the weld pool and penetrate deeper, and since these elements has lower solidification temperatures and high solubility in the melt they are often pushed into the center of the weld, causing cracking after complete solidification. Therefore increasing the strength of the weld can be achieved using the effective throat formula if all the other variables are controlled and taken into consideration.

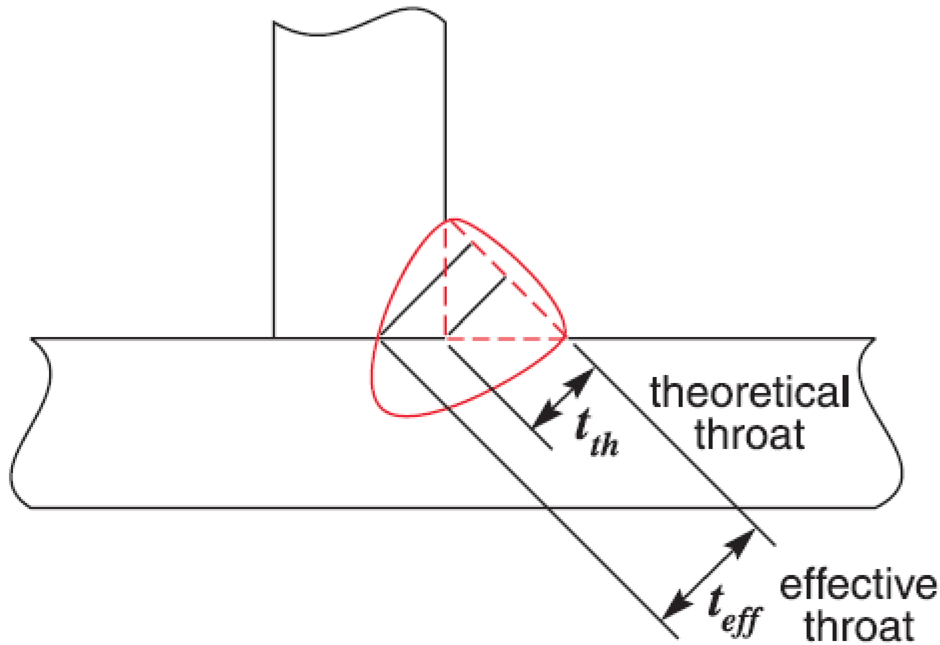

Figure 2.8 Throat size vs. Effective throat size

The second factor is the weld curvature (profile), in general, excessive convexity contribute to stress concentration and may cause early failure when subjected to fatigue loads. Moreover it means too much material usage which is avoidable. Convex welds occur when too high amperage is used or improper electrode travel angle. The best practice is always to achieve a completely flat weld. On the other hand, concave profiles are defined as a lack of material filling the weld surface, adding to a reduced weld throat giving rise to a premature failure. Concave welds occur when too low amperage is used or due to slow electrode manipulation. In a study on weld contour by Chia-Lung [13] it was found that fatigue strength increase with increased weld size i.e. weld throat.

2.9 Sensors in the field of welding

Sensing technology for welding process are broad and involves detecting external regularities during welding either on the work piece side such as inaccuracy in shape, setting and thermal deformation or in the welding process side such as arc light, heat, spatter, bending and breaking of electrode wire, wearing of power supply tip and fluctuations of wire feeding rate and voltage [14]. The prominent feature of this project is the use of the high speed camera in analyzing occurrences in voltages and currents while performing welding tests. The idea of the usage of cameras in the field of welding development can be used in two major ways; for research and development purposes (non-real-time welding process control) and for in-service applications (real-time welding process control). The former to utilize the camera to capture occurrences then the researcher would later analyze the data; this method is mainly used in researching specific issues for instance to record the starting properties as in this project, capturing weld pool dimensions and surface geometry during welding and correlating them to penetration power and parameters chosen for the process. [15]. Or to understand the mechanism of droplet formation using different parameters [8].

The second utilization for the camera is to provide the ability for the welding system to adapt to circumstance changes and uncertain disturbance encountered during welding, giving the system high flexibility and intelligence in other words imitating experienced welders. The camera here is to be part of a feedback loop sensing and tracing occurrences in robotic welding and immediately sending signals to a computer equipped with specific softwares, which then controls welding procedures accordingly, generally used in in-service automated welding systems to improve efficiency. The cameras used here are of different technology named CCD or Charged-Coupled-Devise which is very sensitive to light detection. Numerous applications for CCD cameras have been researched and implemented in MIG/MAG welding and other welding processes; for example:

- To monitor weld depth penetration. [20].
- To monitor and control the upper surface “topface” of weld pool size and correlate it to the back face weld bead size [16].
- To recognize and guide initial welding position of work piece which are points with obvious features such as corners, intersection points of seam and edges etc. [18].
- For tracking seam weld automatically with or without auxiliary light source [19].
- For path correction ahead of the welding torch [17].
- To reconize and position the start welding poistion in order to obtain an autonomous robot welding. [21]

All applications require an image processing algorithm to interpret and control the welding process parameters.

Cameras of the type used in this project are typically used in biomechanics and capturing rapid animal movements. The Camera model used was Photron SA-1 Ultra High Speed Video System which has the ability of capturing images up to 6000 frames per second. The concept behind its use here is to understand what happens in events of current and voltages fluctuations; graphs of currents and voltages are obtained but without any clear explanations. The key contribution of the Ultra High Speed Camera is that it gives an idea of what actually happens as the currents or voltages have abrupt changes, also it shows some welding starting properties as the wire starts descending while feeding and an arc is created. Detailed examples are given in Chapter 4.

Other methods detecting occurrences during welding could be monitoring the wire feedability via feeding-sensors to detect the degree of smoothness of wires yielding a stable arc. And measuring the audible sound with frequencies ranging between 20 and 20,000 Hz, which is produced from the arc in welding processes. Skilled welders highly depend on sound produced in many ways, as it is an important feedback quality for of detecting arc stability and welding quality since it reflects the behavior of the arc and the weld pool. In a paper studying the arc sound characteristics for gas tungsten argon welding it was proven that sound pressure is affected greatly by gas flow, arc length and current [22].

The aim of utilizing all these sensors is to establish a welding system with a stabilized droplet transfer and arc, improved arc orientation, increased deposition rate, increased penetration depth and geometry all within an easily automated welding system.[23]

Chapter 3
Experimental Procedures

The project was divided into three tasks. The first task involved the use of the High Speed Camera and data logger to analyze occurrences during ignition as suggested in the method. The Second was a subjective assessment of the wires' performance and finally the Third was a study of the weld shape and profile. In an attempt to gather more knowledge about MAG wires' behavior; six wires were chosen, four bare wires and two copper-coated, two products from ESAB AB and four from different manufacturers. Usually, in any welding process there exist many parameters to control. Setting the welding parameters is perhaps one of the reasons of the slow development rate of MIG/MAG especially in its implementation in industry [24]. Primarily due to the complexity and the mutual dependence of these parameters among each other; all parameters were kept constant, except for varying:

1. Types of wires
2. Voltage, current and stick-out distanced for the corresponding Short, Globular and Spray arcs
3. All tests were conducted on mild steel samples as base metals

Other parameters that would determine the behavior of welding process or weld performance could be the shielding gas, the power source, the robot, parent material among many others. For simplicity the shielding gas used throughout the tests was CORGON18 consisting of 82% Argon and 18% Carbon Dioxide, hence the name MAG (Metal Active Gas).

The wires test consisted of an array of manufactures of both bare and copper coated wires. In Table 3.1 a description of each wire is cited according to their manufacturers.

Wire#	Coating	Chemical Composition (wt%)					Diameter (mm)
		C	Mn	Si	P	S	
# 1	Copper	0.1	1.5	0.9	-	-	1.2
# 2	Bare	0.1	1.5	0.9	-	-	1.2
# 3	Bare	0.08	1.55	0.85	-	-	1.2
# 4	Bare	0.06	1.1	0.41	0.012	0.011	1.2
# 5	Bare	0.08	1.13	0.6	0.01	0.011	1.2
# 6	Copper	0.09	1	0.59	0.01	0.012	1.2

Table 3.1 Wires Description

3.1 Task #1 High Speed Camera Welding Tests

The aim of this task is to investigate the data of voltage/current relation with time acquired via the data logger and capturing the images with the high speed camera simultaneously. All of this was done with the help of a six-axis robot handling the welding process. The process is called 'weld test', Figure 3.1 below shows a typical image of the weld tests, for Spray (upper row) and Short Arc (lower row).

Figure 3.1 Sample Spray and Short Arc welding Tests

Tests started by installing a wire on the robotic reel and adjusting the stick-out, Wire feed speed, Volts and Amperes as shown in Table 3.2 using Artiso Mig500 as the power source:

	Short Arc	Spray Arc
Stick-out	12 mm	20 mm
Wire feed Speed	4 m/min	10 m/min
Volts	17.3 V	32.3 V
Amperes	180-190 A	300-308 A

Table 3.2 Task #1 Constant Parameters

Installing the high speed camera and the laser beam with the computer and the data logger took roughly a day. After connecting the high speed camera recorder with the data logger to obtain synchronized data the tests were commenced. The laser beam has to be directed towards the wire tip to give proper illumination for the camera since there are very strong interferences from arc light, metal transfer, spatter and other sources that need to be neutralized. For each type of the six wires, four weld tests were conducted for Short and Spray Arcs in order to gather enough material for investigation, hence 48 tests. Each test started with separately triggering the robot, the laser beam, the data logger and the high speed camera. The setting is shown in Figure 3.2.

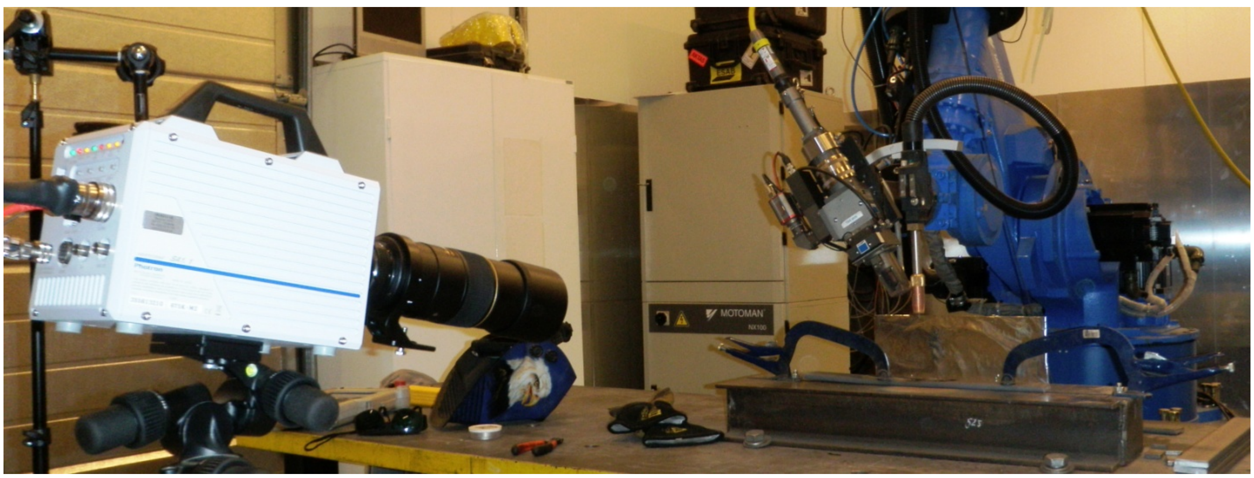

Figure 3.2 Welding Test Setting with High Speed Camera (left), Robot (right), table and work piece (middle)

The Ultra High Speed Camera then records the images, with help of a commercial software; detailed images can be viewed as shown in Figure 3.3.

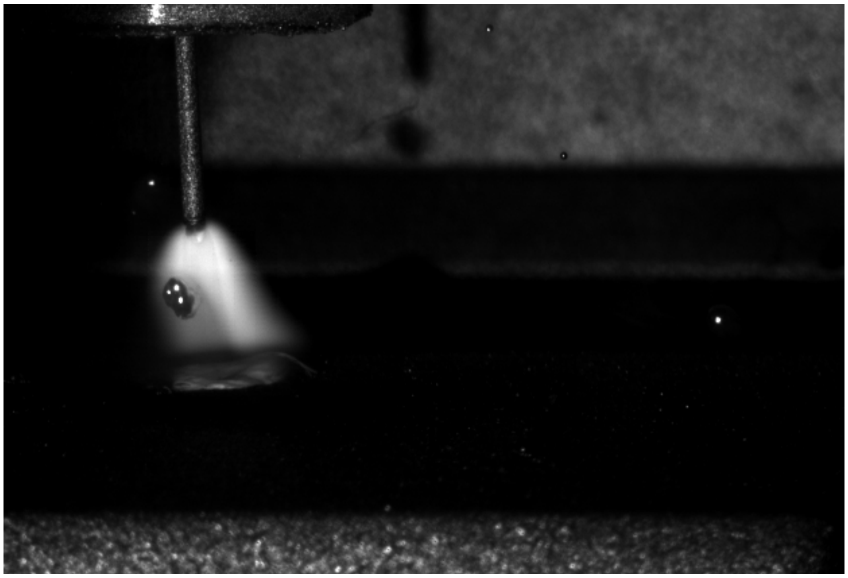

Figure 3.3 Sample Image frame of the HSC

At the same time the data logger saves the acquired voltage and current data signals from the powers source, with the help of a special software DEWESoft 7.0.3 it can be viewed in the form of graphs. A typical data obtained from the data logger Voltage vs. Time and Current vs. Time is shown Figure 3.4. Notice the curve fluctuation as the start of the weld test i.e. unstable arc.

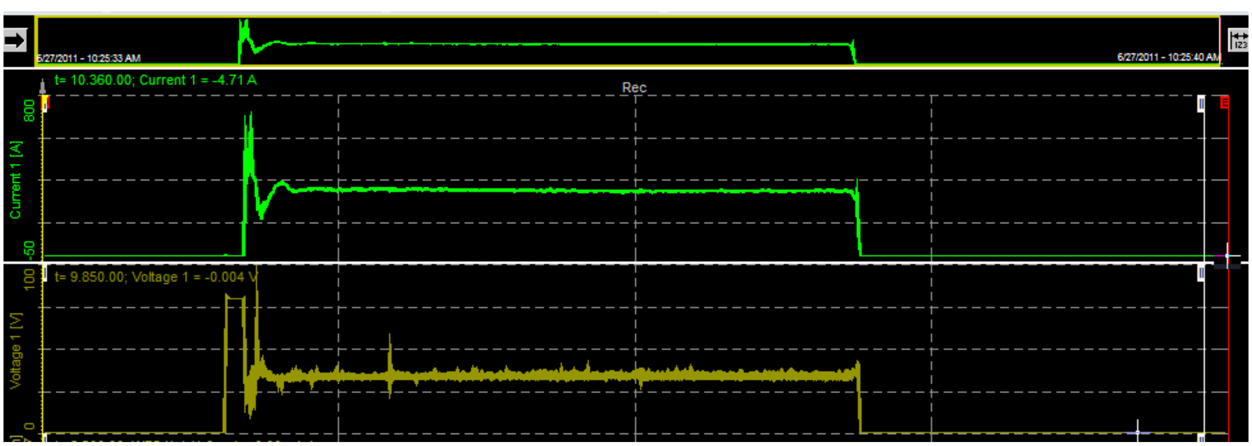

Figure 3.4 Current and Voltage vs. Time sample graph

3.2 Task #2 Manual Welding Tests

The second task involved testing the wires manually; Manual tests are conducted without the help of robots i.e. done manually by welders. The welders' subjective opinion is always of high importance in the welding process evaluation. Observations were documented according to arc type since each of Short, Globular and Spray Arcs have their own applications.

According to ESAB's welding evaluation form (attached at the report end) the following factors are important to consider in evaluating a welding process: wire diameter, welding position, wire feed speed, current, voltage, droplet transfer, arc stability, arc drive/force, spatter level, slag coverage, slag following, slag detachability, weld pool cleanliness, weld pool wetting, bead shape and bead appearance. There exits other factors that would definitely alter the wire performance and starting properties but mainly for time and resources constraints, they were not investigated in this study, for instance the power source or the shielding gas.

The same six wires were used in the tests but with three different types of arcs, Spray, Globular and Short Arc. The weld tests were later cut and molded for the following task, Task #3. The corresponding voltages, currents, wire feed speed and parent metal samples for each arc type are shown in the Table 3.3.

	Short Arc	Spray Arc	Globular Arc
Parent Metal*	1312 Steel Thin	355 Steel Thick	
Volts (V)	15.5	18.7	29
Amperes (A)	134	214	300
Wire Feed Speed (m/min)	3	6	8.5

*Both Steel grades used were mild steel.

Table 3.3 Task #2 Constant Parameters

Notice that for short arc thin steel plates were used as for the relatively lower amount of heat input comparing to Globular or Spray in which more heat input is associated and hence thicker steel plates were used.

Here it is very difficult to focus only on the wire starting properties as it only lasts for a split second since the data logger was not used in manual tests; in turn we focused on the welding process as a whole including the weld performance and shape. A Mig U5000i was used as a power source and a stick-out ranging from 15-25 mm depending on the type of arc desired and the welder's sensitivity, shortest for Short Arc and longest for Spray Arc, while stick-out for Globular Arc lies in between.

3.3 Task #3 Fillet Weld Size Measurements

Finally, the third and last task in this project involved cutting the weld tests samples from the previous task; Task #2 and putting them into molds. Later samples were properly polished then etched. A total of 18 samples composed of six types of wires and three types of arcs for each. As mentioned from the previous task weld tests were performed with Short, Globular and Spray Arcs. An investigation started regarding the size of the weld at constant magnification. The aim of this task is to check how the weld bead size and geometry changed with different arcs for the same wire, and to compare weld beads from different wires of same arc applied.

A single section in the middle was cut from the weld samples to be examined; this in fact was considered as representing the whole sample for each test condition in terms of weld size and profile since visual observations did not show any major changes along the weld.

Vertical leg length was used as an indication of weld strength and integrity as it can be observed and measured on fillet welds non-destructively with visual inspection. While weld Root penetration was used as several papers suggested it as a direct indication of weld strength.

Samples were adjusted under a light microscope at a magnification of 12.5x and with the help of a computer software, a precise measurement of the following values of the weld bead were obtained as shown in Figure 3.5.

1. Leg Length vertically (size of weld)
2. Leg Length horizontally
3. Root of weld
4. Weld Shape
5. Convexity

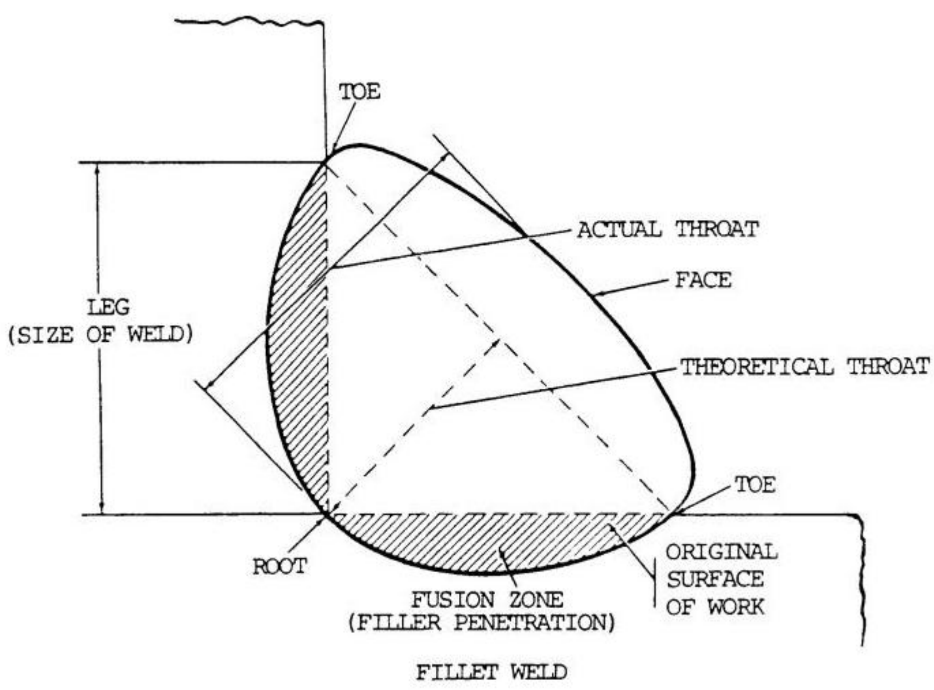

Figure 3.5 Illustrated figure of fillet weld geometry

Chapter 4
Results

4.1 Task#1 Results - High Speed Camera Welding Tests

Apart from the arc initiation part, analysis of the voltage/current data obtained from the data logger showed that the six wires in short and spray arcs had roughly the same behavior during the whole duration of the welding tests. In Short arc voltages ran between 1-30 Volts and currents between 110-300 Amperes, the low voltage value due to short-circuiting as explained earlier in section 2.3.1. For Spray arc voltage had a range of 31-37 V and current 300-320 A. Needless to say that all these values are base values, momentarily the current changes dramatically whenever there is a slight change in voltage.

There were no significant differences between the wires, except for the time it took the welding process to establish a stable arc i.e. arc initial ignition and that was a noteworthy factor that differentiates between wires.

As explained before in section 2.4, the starting properties could be an indication of the degree of stability of the arc when it starts, for instance it will be more convenient to have a wire with minimum time for arc duration resulting in less spatter and less wire consumption. In order to investigate that the duration of the unstable voltages was measured for all wires, the unstable part for all wires was measured in seconds, and the numbers of voltage peaks were counted.

Relating the events that occurred on the data logger graphs with the images from the Ultra High Speed Camera took longer than expected, since both of them were not synchronized, they both did start within the same second, but the data were recorded on milli and micro second scale. After detailed observations, it was possible to relate the images to the data, by correlating the voltage peaks on the graphs to the images. It turned out that whenever there was a voltage peak there was an abrupt melting at the middle of the exposed part of the wire while the rest of the wire is still in solid form, leading to a min-explosion of this tip, hence a flying wire tip that would stick on the work piece or the nozzle tip. Naturally this was obtained by the High Speed Camera captured images. This abrupt-cut or break in the wire will be called wire-cut throughout the project. It probably occurs due to the extreme high voltage subjected to the wire followed by wire resistance, the wire melts locally close to the nozzle, and it explodes away, giving a longitudinal-wire-shaped spatter of few millimeters long. For instance, a sample for Wire #2 weld test, the wire was cut three times giving three peaks on the graph. Captured images of this process are shown in Figure 4.1, where the wire acquires a zero stick-out and its upper tip explodes away. Figure 4.1 illustrates the wire-cut phenomenon. (1)The nozzle tip (2)Wire Tip (3)Cut part of wire (4)Work piece.

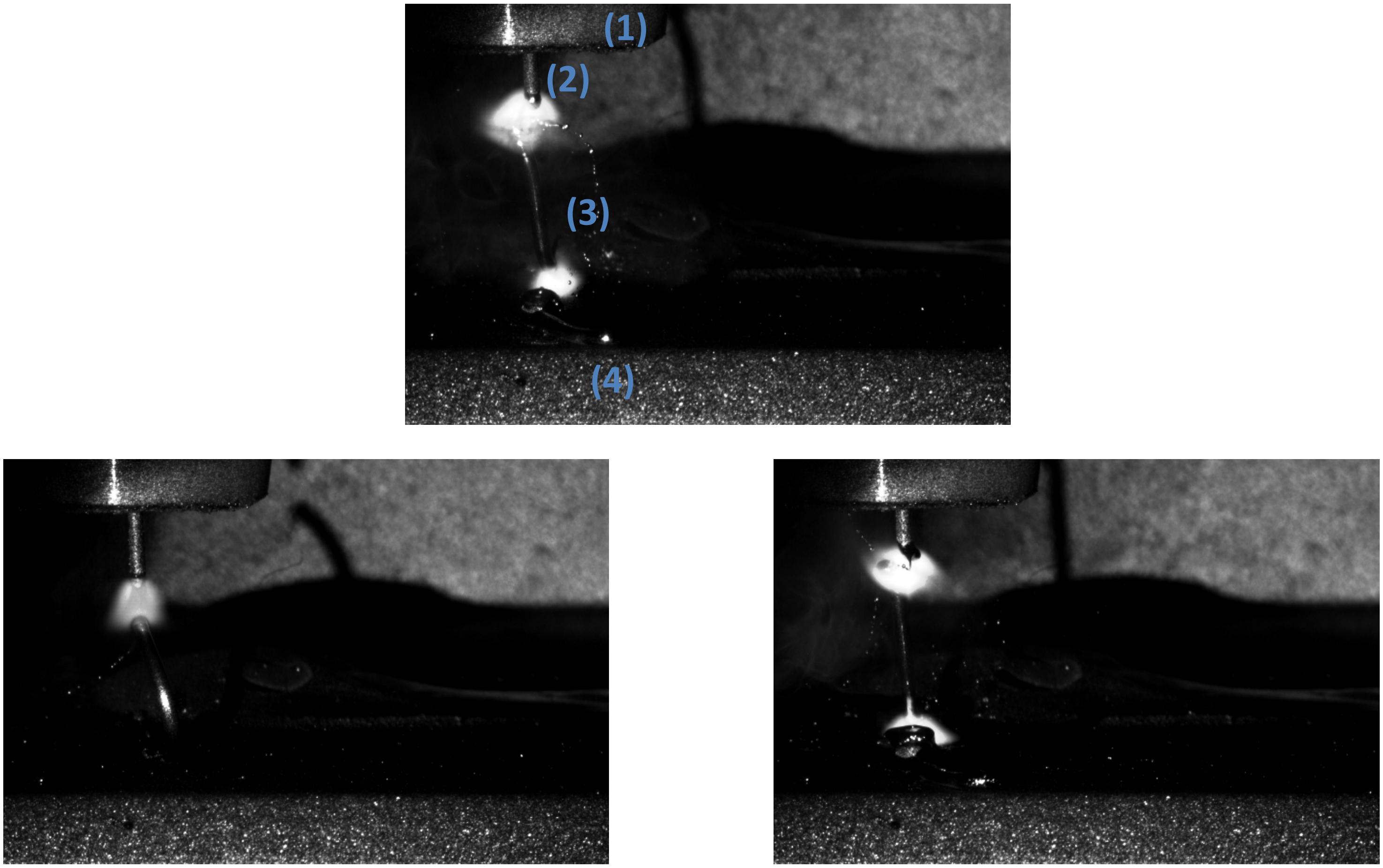

Figure 4.1 Three Consecutive cuts of same wire

The corresponding events on the graph extracted from the data logger are shown in Figure 4.2 below.

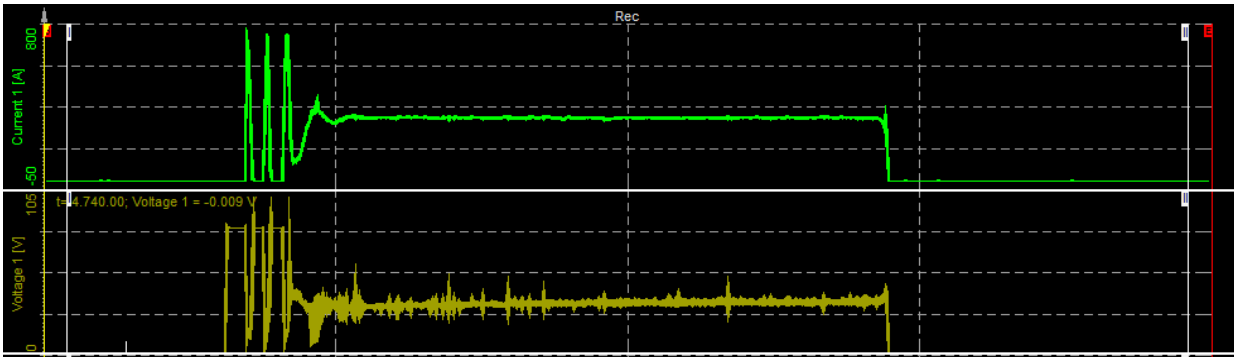

Figure 4.2 The three wire cuts as they appear on the data logger graph

As seen in Figure 4.2 the three voltage peaks immediately followed by current troughs, confirming the assumption that voltage i.e. potential difference, increases as the distance between wire tip and work piece increases, here as the welding process starts with the arc not being established yet, the feed continues until wire sticks to the work piece giving zero stick out and zero arc length (Stick-out illustration in Figure 2.6) with maximum current and minimum voltage values at this point the wire tip breaks and explodes away giving maximum distance between wire tip and work piece (maximum stick-out) with maximum voltage and minimum current values. This process takes place very quickly, usually between 0.6 and 0.9 millisecond for each wire cut and it can happen several times resulting in the three consecutive wire cuts in Figure 4.1.

Another aspect related to wire, is the presence of a solidified droplet at the tip of the wire from previous usage. It was noticed that these solidified droplets have an effect on arc stability starting properties, discussed in Chapter 5. An illustrating image is shown in Figure 4.3.

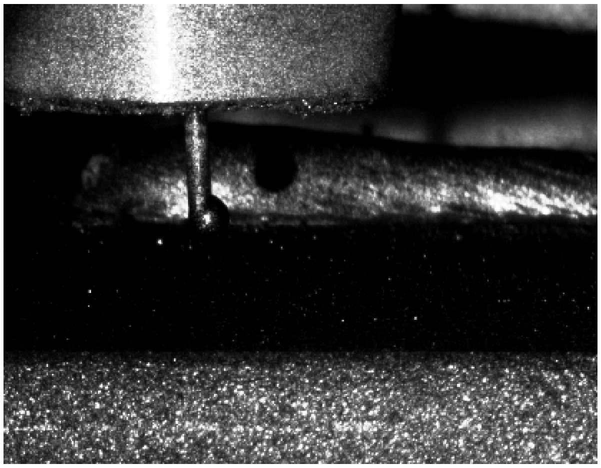

Figure 4.3 A Solidified droplet on wire tip

Although the usage of the High Speed Camera in welding tests widens the possibility and understanding of the welding process and the arc starting properties in particular, it had the following limitations that during operation:

1. It takes a long time to set due to the complexity of the devise and the accompanying laser beam, which might result in eye hazards if protecting goggles were not used.
2. High Speed Cameras can only be used in robotic welding, since the lens must be focused on a specific location not easily achieved with manual welding.
3. Acquiring captured images for a whole welding test is a difficult task due to the enormous amount of data. For instance less than one second of images might result in over 5 GB of memory.
4. The difficulty to synchronize the recorded images with the current and voltage data, though this problem could be fixed with the help of an expert/electronics engineer to synchronize the four devices camera, laser beam, data logger and welding robot.

For obvious reasons results were divided into two groups, Short Arc and Spray Arc.

4.1.1 Short Arc

All weld tests took exactly the same duration of 3 seconds and 91 milliseconds since the process was robotized. The duration of the initial unstable arc for each wire is shown in Table 4.1 below, these durations represents each wire since the variations in unstable arc duration within the same wire were in microsecond thus an average value was taken.

It is obvious that the unstable arc duration differs according to the type of wire. It took Wire #2 the longest period to achieve a stable arc, while Wire #4 took the shortest and both of them are bare (uncoated wires). While for the two copper-coated Wires #1 and #6 both have nearly equal values of unstable arc duration.

Wire #	Unstable Arc (sec)
# 1	0.310
# 2	0.983
# 3	0.502
# 4	0.246
# 5	0.354
# 6	0.340

Table 4.1 Short Arc - Unstable Arc Duration

Analyzing the captured images for each test, the following observations were noted during unstable arc. These factors contribute by one way or another in the duration of the unstable arc:

- The wire tip usually swings back and forth before arc starts i.e. prior to ignition with no evidence relating it to wire cut.
- The shortest duration appears when there are no wire cuts, the duration to reach a stable arc is longer if the wire is cut several times.
- In general, many disruptions take place in Short arc i.e. with every short circuiting giving small amount of spatter every time. With every fall of droplet tiny spatter occurs which doesn't spread but usually sticks directly in/around weld pool and on the electrode tip.
- Wire feed is continuous only when a stable arc is achieved, otherwise feeding is discrete especially at the start, during this time there is a high possibility of the occurrence of wire cut.
- Electrode tip doesn't move along the work piece until a stable arc is reached, to guarantee that a weld pool is established, probably this is feature of the power source.

- All wires had a minor angle shift as feeding starts before any ignition; it is assumed this is due to wires being rolled into wire reels then stored and while in usage wires still retain a curved structure rather than a straight one.
- The presence of a solidified droplet at wire tip (blunt wire tip) before arc initiation guarantees a wire tip cut.
- During arc ignition Wire #5 and #6 have molten droplets falling on regular intervals, that is short circuiting. Droplets falling are synchronized with feed giving a stable arc throughout the test the closest to ideal welding operation among the other four wires.
- Comparing between droplets shape and size in short arc between wires was very difficult since it is based on short-circuiting, the stick out distance was really short to enable monitoring of the shape and size of the droplets.

4.1.2 Spray Arc

Table 4.2 below is for Spray arc tests; robotic weld tests took 3 seconds and 65 milliseconds. All time values represents the unstable arc duration for each wire by means of calculating the average among the 4 welding tests.

Wire #2 had the shortest unstable arc duration, while Wire #5 had the longest among bare wire. Copper coated Wire #1 and Wire #6 have very similar durations. Overall, the variation in unstable arc duration between wires was much less in spray arc than in short arc.

Wire #	Unstable Arc (sec)
# 1	0.564
# 2	0.446
# 3	0.455
# 4	0.475
# 5	0.574
# 6	0.585

Table 4.2 Spray Arc - Unstable Arc Duration

Other observations were noted during unstable arc by analyzing images acquired from the High Speed Camera:

- It was observed that voltage peaks in data logger graphs corresponds to wire cuts as mentioned before, and it contributes to a longer unstable arc duration, that rule applies to all the six wires in Spray Arc.
- Bare wires take shorter time to reach a stable arc than copper wires.
- In general spatters are visible at the start of arc ignition; they vary according to wire type. Wire #6 had a minimum amount of spatter.
- Copper-coated wires had less spatter compared to bare wires
- Same as in Short arcs, wires had an angle as feeding starts before ignition.
- Electrode tip doesn't move along the work piece until a stable arc is reached i.e. to make sure a weld pool is established, probably this is feature of the power source.
- For the shortest duration of unstable arc among bare wires, Wire#2, kept on breaking until a certain stick out was reached, then a stable arc was established. While the longest unstable arc duration, Wire #5 had several wire cuts but after a stable arc was reached it had less spatter and larger droplets fell directly to weld pool.

- Wire#4 had much larger droplets with the highest amount of spatter flying in and around weld pool, while Wire #3 had very small amount of spatter continuously supplied to the weld pool.
- Droplets size and shape were easier to notice in Spray arc, Copper-coated wires had non-spherical droplet shape comparing to bare wires in accordance with what was mentioned in section 2.5 regarding Wire Chemistry, but Copper-coated wires appeared larger in size than bare wires.

4.2 Task#2 Results - Manual Welding Tests

Manual welding tests were divided into tests of short, globular and spray arcs. It is worth mentioning that the features mentioned below were the distinctive ones noticed by the welder and not all the features.

4.2.1 Short Arc

Wire #5 showed an excellent performance compared to the other bare wires, for instance, it had a very stable arc with a normal amount of spatter, soft sound and an appropriate amount of slag. Wire #2 came next with a convex weld bead and minimal amount of spatter and slag, after came Wire #3 and Wire #4 with an irregular sound and rough convex weld, though Wire #4 had smaller amount of spatter.

Wire #6 was the best among copper coated and bare wires. It had nearly no spatter, very small droplets fall directly to weld pool, soft sound with a stable and constant arc throughout. Wire #1 also showed a better performance than bare wires except for Wire #5, it had a stable weld pool with big droplets, small amounts of spatter, irregular fluctuating sound with slightly convex weld bead.

4.2.2 Globular Arc

Wire #2 and Wire #5 were the best ones in general, Wire #5 was very smooth in feeding, very small droplets of melted wire and of spatter with constant arc pressure while Wire #2 was also stable in general with soft and constant arc, reduced amount of slag and an appropriate amount of spatter. Wires #4 had a fluctuating droplet size with some interruptions while Wire #3 had irregular drops, reduced spatter and convex weld shape.

For Copper coated wires, #1 and #6 had a stable arc with some spatter but Wire #6 had convex weld bead while Wire #1 had a more flat one.

4.2.3 Spray Arc

Wire #2 has the best arc stability giving a flat weld bead and some slag. Wire #3 had a very good arc pressure, regular sound with no interruptions and a significant amount of slag. Wire #5 had also a very stable arc, minimal spatter resulting in a flat weld bead. Wire #4 had a rough sound and more slag.

For copper coated wires, Wire #1 had a squeaking noise as the spool roll was giving feed, big slag islands, wider arc, rough sound with some spatter, while Wire #6 had a wide arc, less slag islands, smooth operating sound and a wider operational voltage range giving a flat weld bead.

Slag formations in spray arc are more evident compared to short arc, because of the higher voltage and thus higher material penetration with larger weld pool.

4.3 Task #3 Results -Fillet Weld Size Measurements

Results are dived into two tables according to two criterions. The first is concerned with the shape and convexity of the weld and the other is concerned with the Throat and penetration as mentioned in the Chapter 2. Figure 4.4 shows a sample image of fillet weld as it appeared under light microscope.

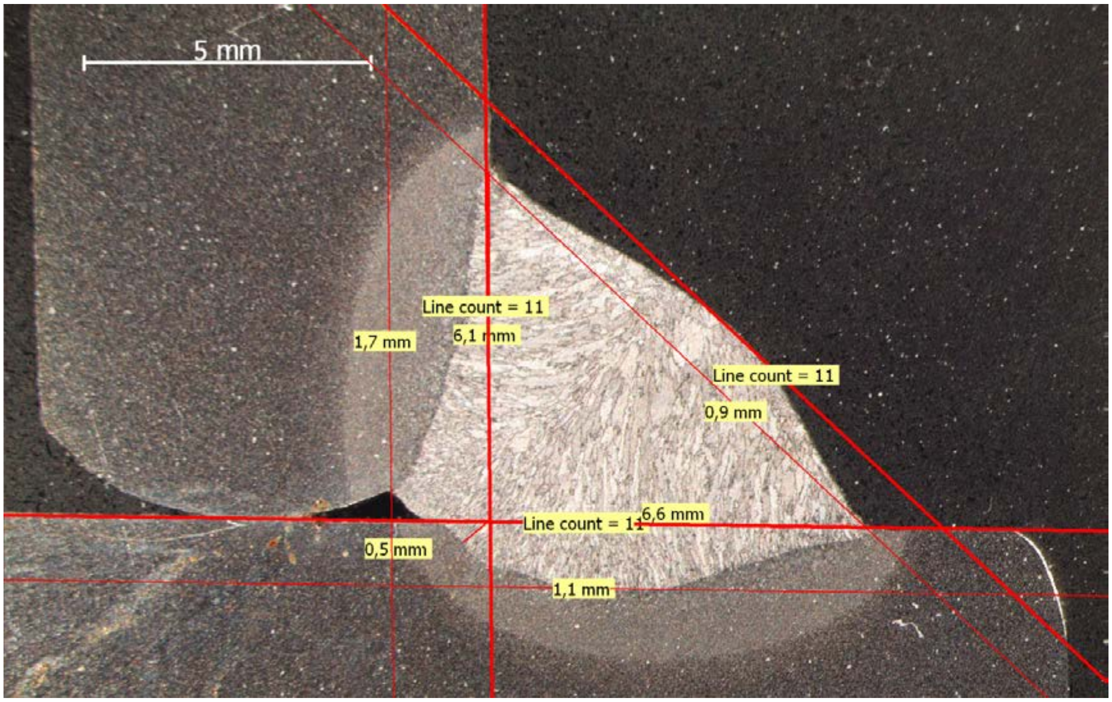

Figure 4.4 Sample Image of fillet weld under light microscope

Samples from Task #2 were cut at the middle section to give representative value for the weld test; naturally values might vary within the same sample but the variations are only within range of less than one millimeter and would not affect the comparison between wires' profiles.

The following tables have values that were acquired from the samples' weld measurements of Task #2, results are divided into Short Arc, Globular Arc and Spray Arc.

4.3.1 Short Arc

Wire#	Weld Shape	Convexity (mm)
1	Convex	0.8
2	Convex	1.1
3	Convex	1.6
4	Convex	0.6
5	Slightly Convex	0.3
6	Convex	0.6

Table 4.3 Short Arc - Weld Shape

The wire having the least convexity is Wire #5 among bare wires, while Wire #6 for copper coated wires has least convexity.

It is obvious here that bare wires had a wide range of convexity values, unlike copper coated wires.

Wire#	Leg Length = Fillet Weld Size (mm)	Horizontal Leg Length (mm)	Throat (mm)	Root (mm)	Effective Throat (mm)
1	4.5	5.8	3.18	0.5	3.68
2	4.1	5.4	2.89	0.3	3.19
3	4.9	4.9	3.46	1.3	4.76
4	4.2	5.3	2.96	0.6	3.56
5	4.7	4.9	3.32	0.9	4.22
6	4.0	6.3	2.82	0.2	3.02

Table 4.4 Short Arc - Weld Effective Throat

The Bare wire with the highest value of effective throat and highest convexity is Wire #3, and it is significantly larger than the rest of the wires, while it is Wire #1 for copper coated wires.

Bare wires have larger effective throat thus a better weld strength than copper coated ones in short arc.

4.3.2 Globular Arc

Wire #	Weld Shape	Convexity (mm)
1	Convex	0.9
2	Convex	0.7
3	Convex	1.3
4	Convex	1.2
5	Convex	0.8
6	Convex	0.9

Table 4.5 Globular Arc - Weld Shape

Here for Globular Arc, Wire #2 has the least convexity, while both copper-coated Wires #1 and #6 have the same convexity.

Wire #	Leg Length = Fillet Weld Size (mm)	Horizontal Leg Length (mm)	Throat (mm)	Root (mm)	Effective Throat (mm)
1	6.1	6.6	4.31	0.5	4.81
2	5.9	6.9	4.17	0.4	4.57
3	6.1	6.5	4.31	0.2	4.51
4	6.1	6.8	4.31	0.4	4.71
5	6.3	7.1	4.45	0.6	5.05
6	5.5	6.8	3.88	0.4	4.28

Table 4.6 Globular Arc - Weld Effective Throat

Wire #5 has the highest value of effective throat for bare wire, while Wire #1 has the highest one in copper-coated wires.

4.3.3 Spray Arc

Wire #	Weld Shape	Convexity (mm)
1	Flat	-
2	Slightly Convex	0.4
3	Slightly Convex	0.3
4	Convex	0.5
5	Flat	-
6	Flat	-

Table 4.7 Spray Arc - Weld Shape

Finally, Wire #5 has a completely flat weld, reducing stress concentrations to minimum. While in the case of copper-coated wires it seems that they were designated for spray arc welding applications, Wires #1 and #6 has completely flat welds.

In general it is obvious that the majority of wires acts best in spray arc, all has slight convexity or flat weld beads i.e. the best attainable weld profile.

Wire #	Leg Length = Fillet Weld Size (mm)	Horizontal Leg Length (mm)	Throat (mm)	Root (mm)	Effective Throat (mm)
1	8.9	9.1	6.292	1.7	7.9923
2	8.1	8.5	5.727	1.4	7.1267
3	7.6	9.7	5.373	1.5	6.8732
4	7.7	8.8	5.444	3	8.4439
5	8.6	9.2	6.08	1.2	7.2802
6	7.3	10	5.161	2.4	7.5611

Table 4.8 Spray Arc - Weld Effective Throat

Wire #4 has the highest effective throat among bare wires, and Wire #1 has a higher value than Wire #6, though their values are relatively close, worth mentioning that Wire #6 has a deeper root.

Chapter 5
Discussion

This section is an attempt to discuss and summarize all results and observations from all three tasks.

5.1 Task #1 Discussion - High Speed Camera Welding Tests

Since over 5 GBs of memory space were required for each test as mentioned earlier, it was not possible to monitor the stable arc behavior (the whole welding test duration) for each wire on the high speed camera. Accordingly the analysis was done only on the initial unstable arc.

The method applied of using the high speed camera to monitor events that occur during welding test with the help of the data logger proved to be fruitful. It showed some occurrences like the wire cuts and the effect of a solidified droplet on the wire tip, both had an influence on the arc ignition stage. The camera had a capability of capturing 6000 frames per second producing images with very high quality, i.e. every frame captures 0.16 of a milli-second. This quality was more than enough for the current investigation, for instance the whole duration of an instable arc ranges between 30 and 90 milliseconds depending on the type of arc used and the occurrence of a wire cut has a span of 0.6 millisecond. Camera capturing quality could actually be reduced to 1000 or 2000 frames per second instead, thus reducing the amount of data acquired and making it easier to handle and allowing a record of the complete welding test.

There was a difficulty in determining the exact duration of unstable arc, the voltage vs. time graph settles down gradually and fluctuations appear every now and then.

As mentioned earlier in Chapter 4, the wire cut prolongs the unstable arc, which in turn delays the establishment of a stable arc. Wires #2, #5 and #6 had the highest number of cuts during the 4 welding tests all in Spray arc; they are prone to wire-cuts more than the other wires. Another issue was that when the tip of the wire is cut it is very common for this tip to stick to the nozzle causing feeding blockage and a necessity for nozzle replacement to regain smooth feeding after several usages.

In some cases as in Wire #4 in Short and Spray arcs and Wire #6 in Short Arc the presence of a solidified droplet on wire tip guarantees a prolonged unstable arc, and thus it is advisable to be removed before welding starts.

The task was conducted on short and spray arcs, and accordingly wires behaved differently, for instance, short arc is characterized with relatively lower voltages and currents and spatter are smaller in size and amount, while Spray arc is characterized by higher voltages and current and spatters are larger. This fact became very clear while testing all the 6 wires, regardless of their coating type.

The unstable arc duration is mostly longer in Spray Arc than in Short Arc, for Wires #1, #4, #5, and #6 took less time in short arc than in spray arc. Variations in duration were less in spray arc than in short arc. Also spray arc welding tests duration were less than short arc but with longer portion of that duration in establishing a stable arc.

Copper-coated wires (#1 and #6) have fewer spatters when compared to bare wires. That was obvious in spray arc due to the longer stick-out distance spatters were visible on the High Speed Camera compared to the short arc with shorter stick-out distance, Figure 5.1 illustrates spatters in Wire #4 (bare) and Wire #6 (copper-coated) as a sample.

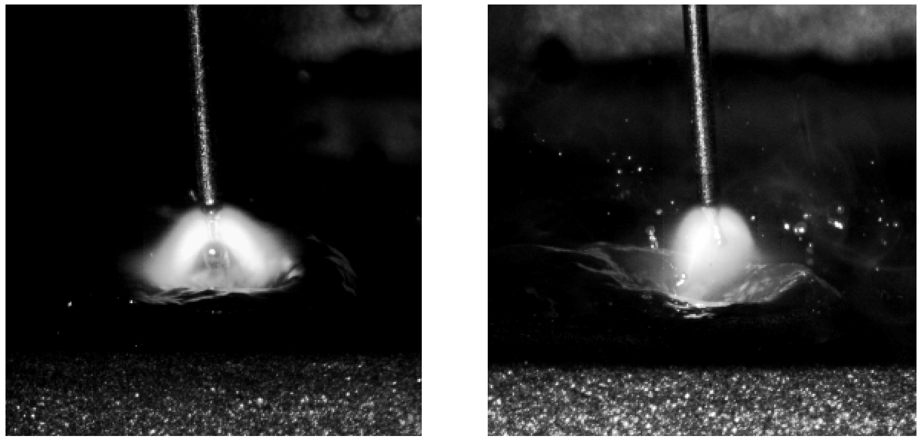

Figure 5.1 Illustration of spatters in Copper-coated wire (left) and Bare wire (right)

Nevertheless short arc is based primarily on short-circuiting and hence spatter is inevitable. It was observed that copper-coated wires have non-spherical droplets, which verifies Kuokawa [10]. Figure 5.2 below shows how a spherical droplet from bare wires and non-spherical droplet from copper-coated wires appear.

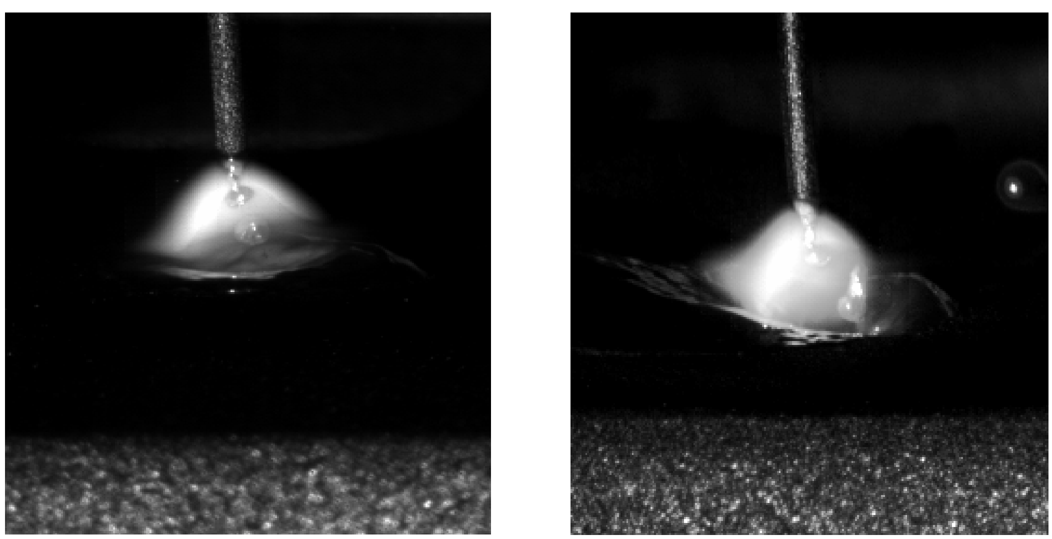

Figure 5.2 Spherical droplet from bare wire (right) and non-spherical droplet from copper-coated wire in (left) – both in spray arc

5.2 Task #2 Discussion - Manual Welding Tests

According to the welder' expertise rough sound with the origin being the wire conduit mounted on the power source during wire rolling/feeding is usually an indication that the wire has a problem with lubrication. As the shift goes from Short to Globular to Spray Arcs the effect of wire lubrication can effortlessly be noticed with increasing wire feed speed. Wire with poor lubrication has a squeaking noise while feeding, Wire #1 produced some noise in spray arc but the noise wasn't noticed in globular or short arcs.

Another important sound is the one produced during initiating and maintaining the arc. This is common for all wires but some wires have irregular louder sounds unlike others, for instance Wire #4 in short and spray arcs was louder than the other wires.

Slag formations were often visible in spray arcs, presumably due to the higher heat input associated with higher voltage. It might also indicate lower compatiblility of wire chemistry with base metal and could be the effect of wire surface lubricant. Wires #1, #3 and #4 showed recognizable amounts of slag islands in spray arc.

It was not possible to determine how long a nozzle contact tip would last before being replaced due to spatter blockage or wire dust (descalling) since all the performed tests combined only lasted for several minutes. In order to tackle this issue the tests needs to be run with wires for much longer periods to achieve a fair comparison. In all, it is taken for granted that nozzles are prone to destruction in case of the presence of lots of spatter and minimum lubrication.

H. Wang [9] concluded that wire feeding is better for bare wires than copper-coated wires, due to the bridge effect of the copper-coating, allowing copper dust to be accumulated on the nozzle (section 2.5) and this was recognized in this project, where Wire #1 (Copper-coated) was the loudest during feeding.

With well lubricated wires, after a while the welding nozzle can be blocked due to spatter accumulation, while wires with rough surface removes collected spatter at the tip, leading to no blockage and an overall smoother weld feed, again this needs a prolonged testing of wires to check its validity.

5.3 Task #3 Discussion - Fillet Weld Size Measurements

It is apparent that the majority of wires have better weld profile in spray arc; all of them had slight convexity or flat weld beads. Though convexity is way better than concavity in weld beads, it is preferable to achieve a completely flat weld. Wires in general operated best in spray arc, convexity values decrease as we go from short to globular to spray arc.

It also appears that some wires were manufactured for specific arc types, comprising between the least convexity and an acceptable effective throat. For instance Wire #5 was the best one in reduced voltage and current specifically short arc, Wire#2 performed best in globular arc and finally Wire#1 was the best in spray arc.

Fillet weld convexity values decrease as the voltage was shifted between short to globular to spray arc. The same thing goes for effective throat and accordingly the strength of the weld, it increases with increasing current and voltage. An explanation for that is the spray arc has a higher heat input and hence deeper penetration producing deeper roots as in [11], but that is a concern when dealing with thin plates, lower heat input would be required instead.

Leg length (filler weld size) can be reduced if the root distance is increased, giving the same strength as indicated by effective throat, this can be achieved by applying higher currents and hence reducing material used and reducing running costs.

5.4 Summary

Given the parameters and the test method used in the project, it is very hard to find an absolute best wire. It was noticed that a shorter unstable arc period does not necessary mean that the produced weld integrity will be the best among wires. Moreover results from Tasks #2 and #3 cannot be fully included in the comparison with Task #1, simply because robotic welding was used in Task #1 and manual welding in Tasks #2 and #3.

However, the methods are complementary, those used in Task #1 (High speed Camera Welding Tests) revealed new aspects as in wires-cuts and unstable arc duration, while results from Task #2 (Manual Welding Tests) and Task #3 (Fillet Weld Size Measurements) verified welders' opinions on wires. High speed camera method can by utilized in a better way, in this project maximum image capturing capacity was used bringing along an enormous amount of data and hence only the start of the welding test could be examined. Fewer images per second could be captured giving the ability to monitor the whole welding test duration opening up more aspects to compare between wires.

Arc and Welding process stability are claimed to be closely related to wire feedability [25], in other words wire lubrication and smoothness. That couldn't be verified by this study as noisy wires gave a good convexity and/or a higher effective throat.

The following is a quick comparison of all six wires, each wire representing a number according to Table 3.1, wires ranking in the following table:
(Bare wires labeled in light-Gray and Copper-coated wires labeled in dark-Gray).

Initial Unstable Arc Duration (Shortest to Longest)						
Short Arc (Range 0.24-0.9 sec)	4	1	6	5	3	2
Spray Arc (Range 0.44-0.58)	2	3	4	1	5	6
Perfomance according to Welder's opinion (Best to Worst)						
Short Arc	5	1	6	2	3	4
Globular Arc	1	2	5	6	3	4
Spray Arc	6	2	1	3	5	4
Convexity (Lowest to Highest)						
Short Arc (Range 0.3-0.6 mm)	5	4	6	1	2	3
Globular Arc (Range 0.7-0.3 mm)	2	5	6	1	4	3
Spray Arc (Range 0-0.5 mm)	1	5	6	3	2	4
Effective Throat Length (Longest to Shortest)						
Short Arc (Range 3.02-4.76 mm)	3	5	1	4	2	6
Globular Arc (Range 4.28-5.05 mm)	5	1	4	2	3	6
Spray Arc (Range 6.87-8.44 mm)	4	1	6	5	2	3

Table 5.1 Comparison of the wires included in this project

From the above table it is evident that:

Initial unstable arc duration in short and spray arcs does not relate to weld bead convexity and effective throat length using the parameters set in this project.

To an extent welders opinion on wire performance matched the weld convexity and effective throat length.

Wires gave different rankings in according to type of arc used.

Also, in Task #1, Wire #4 (bare) had the shortest duration of stable arc formation in Short arc while both copper-coated wires had similar performance.

Task #2, Wire #5 in Short and Globular arcs among bare wires and Wire #6 (copper-coated) had a very good welding performance on Short, Globular and Spray Arcs.

Task #3, Wire #5 was the best among bare wires in Short, Globular and Spray Arcs and Wire #6 was superior to Wire #1.

Chapter 6

Conclusion

To make a quick warp-up of the methodology applied in the project:

1. First: Robotic welding tests, monitoring current intensity and voltage data in short and spray arcs and recording the arc process via Ultra High Speed camera and high frequency data acquisition system.
2. Second: Manual Tests for each wire using Short, Globular and Spray Arcs and documenting the welder's subjective evaluation of each wire.
3. Third: Measurements of the fillet weld size and profile from the previous task to get an idea of the weld integrity and endurance.

The suggested method mentioned earlier in Chapter 1 provided fresh information and uncovered new aspects that were not possible to obtain via other methods. Accompanied by the wire comparisons undergone in Tasks #2 and #3, it further confirmed that analyzing the arc starting properties voltage and current trends can actually be controlled at least by altering the wire composition.

The methodology used in this project for testing MAG wires brought up a massive amount of data, enough to draw a picture of each wire's performance under the given constant parameters. For simplicity and since conclusions from Task #1 interlinked with conclusions from Tasks #2 and #3 all observations are stated together and written down in points.

- Synchronizing captured images with data logger graphs was done manually by detecting the exact timing of occurrences, such as wire-cuts in images with voltage peaks in graphs.
- Camera capturing frequency could be reduced to 2000 fps instead of 6000 fps.
- Wire-cuts prolongs the unstable arc duration.
- During the initial unstable arc wire-cuts are very likely to occur.
- The presence of a solidified droplet on wire tip guarantees a prolonged unstable arc.
- The unstable arc duration is longer in Spray Arc than in Short Arc.
- From Short to Globular to Spray arcs, sound while feeding wires with presumed poor lubrication increases.
- Slag formations were much visible in spray arcs.
- The bridge effect of the copper-coated wires was consistent with feeding noise was noticed.
- It is known that arc and Welding process stability is closely related to wire feedability [25], in other words wire lubrication but no indications during the tests confirmed that.
- Welding nozzle contact tips are subjected to destruction in case of lots of spatter and minimum wire lubrication.
- Fillet weld convexity values decrease as we go from short to globular to spray arc, same thing goes for effective throat and accordingly to the strength of the weld. It increases with increasing current and voltage as could be expected.
- It is very hard to find an absolute best wire with the given constant parameters and method used, but it is possible to draw a complete picture of the wire performance.
- It is obvious that wires behave differently according to the type of arc used.
- An interesting phenomenon was detected that the shorter unstable period does not necessary mean that the weld root penetration i.e. weld integrity would be higher.
- The data logger can also be utilized in a better way, the device can receive signals from wire feed speed and sound noise levels for example, they later can be plotted on graphs and analyzed

- Some wires appear to be manufactured for specific arc types.
- Wire #5 and Wire #6 are from the same manufacturer and they performed better than other wires in some conditions.
- Wire feeding is better for bare wires than copper-coated wires as feeding noise were only heard with copper-coated wires.
- Copper-coated wires have fewer spatters when compared to bare wires.
- In general it is obvious that the majority of wires act best in spray arc, all has slight convexity or flat weld beads.

Chapter 7
Suggestions for Future Studies

For Future studies and research the following is suggested:

- The presence of top notch technologies as in the high speed camera could open new doors for wire and power source improvements.
- A chemical analysis to be made on the wires and a study of the wire surface as a continuation of the methodology testing.
- Moreover, this project was only concerned with the starting properties of the wires i.e. the unstable part, and so other studies must be made to analyze the uniformity of the voltage/current cycle with time. Also there exits another unstable arc duration as the wire is extinguished and it too should be tackled.
- Microstructure should also be examined for the weld beads along with fatigue and tensile testing to confirm weld strength due to penetration.

It is worth mentioning that there were some limitations encountered during this project, for instance:

- The project required some heavy softwares for data extraction and analysis that needed a stronger processor than the common laptops in the market, several computer break-downs were encountered during the project's data analysis. Needless to say that a several hundreds of Gigabytes were essential for storing of the captured images.
- The method used required skilled expertise in operating the high speed camera and data logger and triggering them simultaneously.
- Synchronizing between camera, data logger, welding robot and laser beam required at least 3 persons present, moreover the captured images and data logger graphs had to be synchronized to detect occurrences.

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ESAB

WELDING EVALUATION FORM

DATE: ____________ EVALUATOR(S): ________________ INDUCTANCE SETTING ____________

POWER SOURCE: ________________ POLARITY: ______ GAS TYPE: ____________

PLATE TYPE: ________________ THICKNESS: ______ MM TRAVEL/WELDING SPEED: ______ MM/MIN

RATING: 1=VERY POOR TO 10=PERFECT WEAVING: ______ MM STICK-OUT ± ______ MM

PRODUCT NAME:				
LOT/HEAT#:				
DIAMETER (MM):				
WELDING POSITION:				
WFS (M/MIN):				
CURRENT (AMP):				
VOLTAGE (V):				
DROPLET TRANSFER:				
ARC STABILITY:				
ARC DRIVE/FORCE:				
SPATTER LEVEL:				
SLAG COVERAGE:				
SLAG FOLLOWING:				
SLAG DETACHABILITY:				
WELD POOL CLEANLINESS:				
WELD POOL WETTING:				
BEAD SHAPE:				
BEAD APPEARANCE:				
TOTAL:	0	0	0	0
COMMENTS:				