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The Characteristic of Cold Metal Transfer (CMT) and its application For Cladding

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Basic Definition

Surface cladding: the addition of one material to the surface of another in a control manner.

Welding: a fabrication or sculptural process that join or clad material usually metals or thermoplastics by creating weld pool.

Failure: the event when a required function is terminated (exceeding the acceptable limits).

Fault: the state of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources.

Acronym

CMT	Cold metal transfer
GMAW	Gas metal arc welding
TMAW	Tungsten metal arc welding
ALC	Arc length correction
DC	Dynamic correction
WFS	wire feed speed
TS	Travel speed
HAZ	Heat affected zone
WC	Tungsten carbide
HV	Vickers hardness
MIG	Metal inert gas
MAG	Metal active gas
TIG	Tungsten inert gas

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Abstract

Corrosion and wear has been a major challenge in most of our industries. CMT process has been selected as a weld technique because of its low heat inputs that makes it a promising technique for industrial application. However, the aim of this thesis is to study the competence of CMT welding process in cladding of mild stainless steel and performing a qualitative fault tree analysis. Furthermore, the most critical aspect of anticorrosion overlay, such as penetration into the substrate and level of dilution, that usually comprises the essential corrosion resistance of the coating, were analysed.

In the first stage of this thesis, literature review of the welding process, CMT, synergic line and welding defects was discussed. In the second stage, two experiments and various tests have been carried out. The result demonstrates that with Corocarb Ni –WC wire filler, an increased in wire feed speed to 6m/min in test 2 and adjusting of arc length correction (ALC) and dynamic correction (DC) parameter, there was probably dissolve in carbides present in the bead for stringer motion and single bead. Moreover, the level of hardness achieved while adjusting ALC and DC value, for wire feed speed variation from (5-11m/min) is (HV_1 356 - 393) for test 4. In fact, for test 4 straight beads were not produced. Finally, in test 5, the shielding gas was changed, the bead went quite straight and the melt spread well. Comparing, CMT process to Pulse MAG in test 5, CMT process gives hardness value of 422HV_1 and deposition rate equal to 3.3kg/hr. Also, CMT process produces small dilution and no cracks while pulsed MAG produced significant crack.

Furthermore, with Inconel 625, the arc power calculated from average current and voltage related well with the AIP value that were determined by oscilloscope while adjusting parameter ALC and DC are around the middle of the scale. However, with respect to the results, it is advantageous to use large negative value of DC. DC Value of -5 did not probably produce spattering, but it increases melting range, contact angle values, without significant effect on penetration and dilution. Moreover, positive value of DC value does not show positive effect. Also, it is possible to set WFS to 10m/min, this will give the same result instead of bringing more heat to the system.

Keywords: cladding; CMT; DC; ALC; WFS; Oscilloscope; Pulse MAG; wire filler.

1 Introduction

This thesis is to investigate the use of Cold Metal Transfer (CMT) – Cladding in producing wear and corrosion resistant coatings. The goal is to study and investigate this relatively cost effective process in overlay welding and to optimize the operating parameters of the cladding to a certain base and filler wire materials. The experiment data of the CMT cladding are collected from Centria University of Applied Science. This thesis is a part of collaboration project called Interreg involving UIT, Norway, LTU, Sweden, Centria, Finland, Tampere, Finland, and companies from northern Europe and Scandinavia.

1.1 Research Background

The combined effects of wear and corrosion and their different forms cost an estimate of $2.1 trillion annually worldwide for early replacement, lost production, poor performance and damage (Jansson, 2015). Close to one third of these costs can be avoided by extensive application of wear and corrosion resistant materials. This can be related to mining, oil and gas, offshore, steel and metal industries that the conditions are very harsh for materials. Because wear and corrosion are surface related issue, surface engineering is very important when combating such issue. In surface engineering, overlaying welding is a group of coating methods that is used to manufacture fusion bonded thick metallic and metal matrix composites (MMC) on metallic substrates that involves different degree of deposition rate, coating thickness, dilution and heat input. Demands for more material, energy and cost effective overlay welding processes has boost the demand for processes that can produce low diluted and fusion bonded single layer coatings.

However, the market call of cladding/overlaying will probable rise from $3.8billion to $7.8 billion within the next 3 years (Jansson, 2015). This is due to increasing popularity of remanufacturing, in demand to replaced expensive bulk material with coated structure and operating conditions that are needed in many applications. For example, there is increasing demand for increasing productivity in mining and crushing operation that yield more wear resistant materials. Secondly, mineral, oil and gas deposit needed to be dig/drilled from deeper water and ground. Laser cladding with coaxial powder feeding has been the only industrial method to produce low diluted and fusion bonded single layer coatings. Addictive manufacturing/welding has increased its potential in the last three years, meaning adding extra material on each other to achieve it desire aim. The major advantage of additive manufacturing is to lower carbon footprint due to material saving and manufacturing techniques (Jansson, 2015). Though, an advanced metal arc welding are processes with new possibilities to manufacture low diluted single layer coating and near net 3D component with good accuracy, high productivity and low heat inputs are increasing.

Surface cladding, or overlaying welding is often referring to a situation that a layer of material is apply to a carbon or a low alloy steel to provide a corrosion resistant surface. Hardfacing is a little bit different where a resistant material is applied to a material surface protecting the material for a different kind of wear (abrasion, impact etc.). Material layer still have other protecting features such as corrosion. Buttering is quite different, it is applied to surfaces before final top coat. This process is done because of metallurgical reasons. If the metallurgical properties of the base material and the top material are dissimilar and cladding will not be appropriate (Mellor, 2006).

The major pros of overlay welding are the protection of the material surface properties that includes e.g. resistance to wear, hardness, erosion, corrosion etc. The fusion between the clad/coat with the base material is the biggest achievement, the coating does not separate from the base material. The thickness of the coat on the base material can be easily control depending on the coating method applied, even multiple layer can be applied depending on the requirement. There might be some negative side effect that includes the change in base material. The heat of the process alters the composition of the material in the heat affected zone (HAZ). The width of the HAZ depends on the heat brought by the cladding process. This result in changes of the composition that affects the hardness and strength of the HAZ. High dilution and clad penetration can probably reduce the hardness of the coating which makes the prediction of the lifetime of the component difficult. Figure 1 is an example of HAZ. Cracks caused by transformation and heat may be as a result of unexpected corrosion or wear behaviour. For this reason, overlay welding is very sensitive for different parameters controlling the process and thorough test is required when applying coating to new application. The high heat input can cause geometric change to the base material such as bending in thin components. In Figure 1, the overlay weld is manufactured by plasma transfer arc (PTA) welding with a nickel-based powder with tungsten carbide particles on a cold worked tool steel. The HAZ extend deep into the material, the penetration and dilution are quite high.

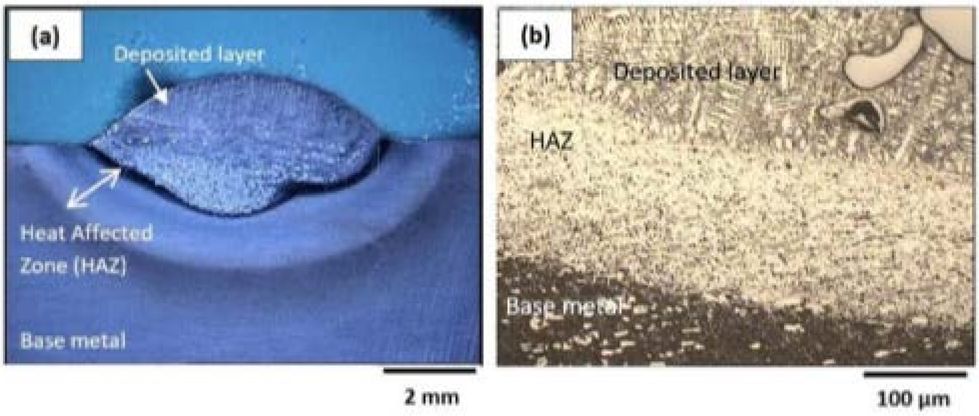


Figure 1 : (a) Macrostructure, (b) Microstructure of one weld overlay bead with different zones visible. Manufactured with plasma Transferred Arc Welding (PTA) adapted from Tahaei et al. (2016).

Cold metal transfer (CMT) process is a highly developed version of Metal Inert Gas/ Metal Arc Gas (MIG/MAG) arc welding process with a precise process control and low heat input to the base material. It is a revolutionary of welding techniques, inclusive of welding techniques and its application. CMT is not only completely new process but also allow application that are as yet completely unexplored. The limit of use of the GMAW can finally be completely faded away, allowing a window of use that is unthinkable to date. Although the evolution of Gas Metal Arc welding (GMWA) technology is more significant for automation and control of welding (Hudson, 2004, Liratzis, 2007). fronius (2005) revolutionary arc welding was introduced, a new arc welding identified as cold metal transfer (CMT). In reality CMT refers to GMAW process with the main difference being the heat input in comparison to the characteristic and well known short arc process. The major benefit of this new process is the possibility of simultaneous dip transfer and pulse arc welding and heat input lower than the conventional MIG/MAG welding (fronius, 2005). The special motion system for controlling the wire speed is incorporated into waveform control and assist in controlling the molten metal detachment and arc length. As explain in fronius (2005), when the arc plasma is developed the filer moves towards the weld pool until the wire touches the weld pool and short circuit takes place, in which the current becomes lower and the electrode is retracted enhancing the droplet detachment. The most recent application of the new process is joining of aluminum alloy with steel and a new range of application is possible with this new process (Bruckner, 2005, Pickin and Young, 2006).

1.1.1 Motivation for the Research Project

Addictive manufacture is a technology that has promised to reduce part cost by reducing material wastage and time to market. Additionally, addictive manufacturing can also encourage an increase in design freedom, can also facilitate potential weight saving as well as encouraging the manufacture of complex assembly formerly made of several subcomponents (Cotteleer and Joyce, 2014). The main business driver for the adoption of this method is freedom of design, customization and possibly reduced time to market (Coykendall et al., 2014). The benefit associated with the reduction in material waste is already limited because the mass of the component is already low to begin with. Whilst the essence of topological optimization of certain component is necessary, there is certain reduction for the material waste of certain component for the following reasons. Firstly, for the increasing usage of carbon fiber with reinforced polymer, aircraft designers were forced to move from the usage of aluminum to titanium, aluminum being electrochemically incompatible with carbon (Vargel, 2004). Secondly, with the current expansion rate of aircraft market the demand for titanium parts is increasing accordingly (Cui et al., 2011). Thirdly, titanium parts are expensive material to source for and machined (Lütjering and Williams, 2003). Therefore, in the aerospace industry there is a pressing move for the development of a process that could replace the current method of manufacturing large structures such as stiffened panels, wing ribs and cruciform etc.

In contrast the use of light material has become necessary because of the need to reduce environmental pollution. The used of this light material is mostly used in automobile industry (Haraga, 2000, He et al., 2008, Hudson, 2004, Larsson, 2003). Because aluminum alloy is light and can be recycle new cars produced from aluminum are under rapid development and some product are already in the market. Though the welding of thin Aluminum is the key problem that facilitate the use of Aluminum and guaranty the property of the car made from aluminum alloy. Conventional MIG welding method is commonly used in joining of thin aluminum but the lack of control over burning through discourage its application in this field.

Short circuiting method is a suitable method in joining of thin aluminum because of its low heat input characteristics (Hermans and Den Ouden, 1999). However, its excessive spatter during welding also gives manufacturers big challenge. This brought about the development of CMT welding technology owing to the no-spatter welding process and low thermal input. Hence, fronius Cold Metal transfer (CMT) is a modified MIG variant, that relies on controlled dip arc transfer mode mechanism, that is supposed to deliver bead with excellent quality, low thermal heat input and nearly without spatter (Williams et al., 2016). Moreover, it meets this expectation when depositing materials such as aluminum and steel, unfortunately, this process is affected by arc wandering in titanium, which result in surface roughness (Shinn et al., 2013). However, tungsten inert gas and plasma arc welding is currently used for welding titanium deposition. These process rely on external wire feed for continuous deposition, the wire must be fed always from the same direction that requires rotation of the torch thus complicating robot programming (Martina et al., 2012). Additively manufactured aluminum is affected by porosity but it has been shown that using good quality welding wires and a certain synergic operating modes, porosity can probably be eliminated (Cong et al., 2015). Fronius CMT in its pulsed advanced mode is of great benefit, due to its low heat input, fine equiaxed grains and effective oxide cleaning of the wire (Cong et al., 2015). Apart from titanium and aluminum; steel, invar, brass, copper and nickel have been deposited successfully. With respect to each material, the focus is on assuring mechanical properties and eliminating defects such as porosity. Residual stress is another major challenge in additive manufacturing. The significant heat associated with arc source leads to high residual stress that are manifested to distortion when the component is unclamped. Residual stress is associated with cooling and is large along the area of deposition (Colegrove et al., 2014).

1.1.2 Research Question

Based on the above discussion, the main problem of the research study is to identify the challenges involves in cladding and additive manufacturing with the CMT process. In addition to identify the benefits and advantages over conventional process (GMWA, TMWA). The following question are posed based on the research challenges:

1. What are the major advantages of CMT over the conventional welding process (CMT, GMWA & TMWA)? What are the main causes of uncertainties in Cladding and additive manufacturing with CMT?
2. Investigating different parameter tests with hardfacing material?
3. Carrying out failure analysis, for investigating various degradation and failure modes?

1.1.3 Research Purpose and Objectives

- To study Cold Metal Transfers (CMT's) welding process competence in cladding and additive manufacturing.
- To examine the process characteristics of the synergic (CMT) process for CMT cladding of stainless steel.
- To perform qualitative failure analyses, using fault tree analysis (FTA).

1.1.4 Research Outline

The structure of this thesis is presented in Figure 2. The first chapter is introduction starts with description of background and motivation of the research. The rest of the thesis is organized as follows: Chapter 2 Research Methodology, Chapter 3 Theoretical Framework, Chapter 4 Equipment and Experiment, Chapter 5 Discussion of Result, Chapter 6 Conclusion, Chapter 7 Research Contribution, and Chapter 8 Suggestion for further research.

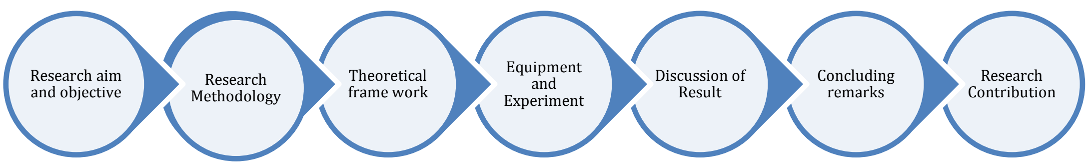


Figure 2 : Research framework

2 Research Methodology

This section of the thesis provides a brief description of the research methodology, approaches and method for data collection and data analysis which assist in achieving our optimum research objectives. Research has been defined in many ways but the like of martyn Shuttle worth – ‘’*In the broadest sense of the word, the definition of research includes any gathering of data , information and facts for the advancement of knowledge*’’(Shuttleworth, 2008). Creswell (2013) gave another definition of research which states that - ‘’*Research is a process of step used to collect and analyse information to increase to increase our understanding on a topic or issue*’’ it consist of three steps pose a question, collect data to answer the question and present answer to the question (Creswell, 2013). Sumser (2001) referred to research methodology as the link between thinking and evidence.

Research can be classified into applied research and basic research. Basic research is carried out to understand the fundamental nature of a subject or topic, that can create new idea and fundamental knowledge (Young and Schmid, 1966). Applied research concentrate on a specific concern or provide solutions to problem (Young and Schmid, 1966). Applied research usually mean a quick, provide a small scale practical result that are usually used for a short period (Neuman and Kreuger, 2003). Choosing a clear methodology is the most and crucial step in carrying out research.

The methodologies that was employed, in this thesis, are both descriptive and exploratory. Moreover, in this thesis both deductive and inductive research approaches will also be applied. The research started as a deductive approach with a literature review to gain a deeper understanding about traditional surfacing and additive manufacturing techniques, pros and cons of conventional welding process and CMT, etc. Furthermore, both qualitative and quantitative research methodologies will be employed in this research. Quantitative research deals with calculation of failure analysis for investigating various degradation and failure modes. Qualitative analysis deals with collection of experiment data, from Centria University of Applied Sciences and, evaluation of conventional surfacing and additive manufacturing techniques and, the importance of CMT technique. In addition, for this research study, case study research strategy will also be used, for understanding the application of CMT products for industries in the northern Norway, Sweden and Finland.

2.1 Research Purpose

Research involves a detail and systematic of phenomena to, broadly and gather information’s and test theory. Get-together of data’s can be for exploratory or descriptive purposes. While theory testing could be exploratory or predictive purposes (Ayele, 2013). A researcher must decide what kind of research should be embarking on. Research can be hypothesized as exhibiting one or more of the following four purposes: Exploratory such as exploring, uncovering and discovering; Descriptive such as summarising, gathering of information and mapping; Explanatory such as testing understanding of casual relations; predictive such as predicting what might happen in various process. Table 1 shows summary of different research purposes.

Table 1: Different kind of research purposes adapted from Neuman (2003)

Exploratory	Descriptive	Explanatory
- Become familiar with the basic facts, setting, and concerns. - Create a general mental picture of conditions - Formulate and focus questions for future research - Generate new ideas, conjectures, or hypotheses - Determine the feasibility of conducting research - Develop techniques for measuring and locating failure data	- Provide a detailed, highly accurate picture - Locate new data that contradict past data - Create a set of categories or classify types - Clarify a sequence of steps or stages - Document a casual process of mechanism - Report on the background or context of a situation	- Test a theory's predictions or principle - Elaborate and enrich a theory's explanation - Extend a theory to new issues or topics - Support or refute an explanation or prediction - Link issues or topics with a general principle - Determine which of several explanations is best

This research tries to explore efficient ways to produce a highly quality weld overlay coatings component using cold metal transfer process. Furthermore, CMT- cold metal transfer is a highly developed version of MIG/MAG arc welding process with a precise process control and low heat to the work piece. This research can be categorized as applied research and the methodology used for this research is both exploratory and descriptive. Moreover, the purpose of this research is to analyse the methodology for obtaining an efficient overlay with a well-controlled welding process different from the conventional ones. Additionally, to describe the methodologies of identifying a quantifying variation in parameter that affects the weld bead. Lastly, to identify weld defect with respect to welding parameters.

2.2 Research Approach

Research approach refers to the methodology or approach that has been adopted to conduct a research (Ayele, 2013). It basically involves the conceptual framework that has been adopted, selection of research questions and the selection of appropriate research method such as primary research, secondary research etc. (Ayele, 2013).

Research approach can be one or encompasses of the following four methods: inductive, deductive, abductive and reproductive. The aim of inductive approach is to establish descriptions of characteristics and patterns, the approach starts by collecting data on characteristic and/ or pattern and its concluded by relating this to the research questions (Blaikie, 2009). The aim of deductive approach is to test theories and eliminate the false ones and validate the survivals. It begin by generating a theory and deduce hypothesis from it and starts testing of the hypothesis by matching then with data explanation from that context (Blaikie, 2009). Abductive is the combination of inductive and deductive approach. For the abductive approach, research can begin with deductive approach, and also an empirical collection of data based on theoretical frame work can commence, this can be finalized by inductive approach in which the theories based on previously collected empirical data are developed (Neuman and Kreuger, 2003). To discover a fundamental mechanism and to explain an observed regularity is the main aim of reproductive approach. The abductive approach create, deductive explain and inductive verifies (Neuman and Kreuger, 2003).

Research approach can be quantitative, qualitative and mixed. Quantitative research refers to systematic empirical investigation of phenomena via statistical, mathematical or computational techniques(Given, 2008) whilst qualitative uses questioning and verbal analysis (Sullivan, 2001). Mixed research method is an approach to professional research that adopt the collection and analysis of both qualitative and quantitative data (Creswell, 2013). Mixed research uses both deductive and inductive approach, uses both quantitative and qualitative data. It attempts to corroborate and complement findings and takes a balance approach to research, meaning it has complementary strength and non over -lapping weakness (Creswell, 2013).

In this research, both inductive and deductive approach is implemented. The research start with deductive approach with a literature review to gain deeper understanding about different welding technology in cladding most especially our area of interest CMT. In addition, different type of hardfacing material was studied. Deductive approach is used to develop a suitable hardfacing material for cladding and obtain a suitable welding parameters and synergy line for cladding, whereas induction approach is applied to quantify the suitable welding parameters suitable for cladding like Arc length correction (ALC) and dynamic correction (DC). Furthermore, quantitative and qualitative analysis has been applied on this research. Quantitative research deals with calculation Arc power, dilution and weld penetration. Qualitative approach was used in performing failure analysis. As the research study tries to mix both quantitative and qualitative methods, and also uses both deductive and inductive methods, this can probably be characterized as having an abductive – mixed research approach.

2.3 Research Strategy

A research strategy is a procedure for achieving an intermediary research objective, refers to as sampling, data collection and/or data analysis (Creswell, 2013). Thus, we can have sampling strategies or data analysis strategies. Creswell (2013) stated that the use of multiple strategy to help construct validity is now advocated by most methodologist. Thus, mixing or integrating research strategy (quantitative/qualitative) in some or all research is now considered a common feature of all good research (Brannen, 2005). Because of the purpose of research and research question, choosing of research strategy depends on what kind of information the researcher is looking for (Yin, 2013). Yin (2013) present five research strategies presented while collecting and analysing empirical evidence. They are: archival analysis, history, experiment, survey and case study. Archival analysis and history strategies refers to the past conditions of the case under study (Yin, 2013). The rest of the strategies (experiments, surveys and case studies) usually refers to present situation (Yin, 2013).

2.4 Data Collection

For each one of the following research approaches, one or many data collection techniques may be used (Straub et al., 2004). Naturally, a researcher will consider one or multiple data collection technique is thinking of using, whilst considering its overall appropriateness to the research, considering some other practical factors such as the expected quality of the collected data, estimated costs, predicted non – response rates, expected level of measurement errors, and length of the data collection period (Lyberg and Kasprzyk, 1991). It is expected that a specific research question may not be well studied because specific data collection technique may not be placed available to achieve the answers to research question (Kerlinger and Lee, 1986). The most popular data collection techniques include: surveys, secondary data sources or archival data, objective measures or test and interviews (Yin, 1984). The data used in this study have been conducted at the research centre in the Centria University of Technology.

Several meetings were held and seminar which this data were discussed and analysed. The research was funded by Interreg North 2020, Troms County.

2.5 Data Analysis

Data analysis can be perform by inspecting, transforming and modelling data with the aim of highlighting important information, recommending conclusion and supporting decision making (Ayele, 2013). Data analysis can be divided into two part exploratory data analysis (EDA) and confirmatory data analysis (CDA) (Ayele, 2013). EDA concentrate on establishing new features in data while CDA confirm or falsify existing hypothesis (Ayele, 2013).

In this research the analysis of the influence of ALC and DC parameter was carried out. The positive and negative effects on other welding parameters and bead shape has been carefully analysed that can be seen from Table 2 has one example.

Table 2: Arc Characteristic values.

	DC	Average			AIP [W]	Diff. I x U vs. AIP	Heat input* [J/mm]	Actual WFS m/min	Power Ratio** [W/mm^2]	Arcing ratio		Freq. [Hz]
		I [A]	U [V]	I x U [W]						Arcing %	Short IRC. %	
ALC -30%	-5.0	195	13.5	2628	2654	-1.0 %	159	8.7	270	43	57	72
	-2.5	181	12.8	2317	2569	-9.8 %	154	8.1	281	43	57	70
	0	167	12.6	2109	2354	-10.4 %	141	7.6	274	42	58	69
	+2.5	153	12.2	1867	2219	-15.9 %	133	7.1	277	41	59	68
	+5.0	139	11.9	**1661**	**2084**	-20.3 %	125	6.7	276	41	59	67
ALC -15%	-5.0	199	14.5	2893	2885	0.3 %	173	9.0	284	49	51	79
	-2.5	188	14.1	2651	2733	-2.5 %	163	8.6	280	47	53	78
	0	175	14.0	2447	2645	-7.5 %	158	8.2	286	48	52	76
	+2.5	162	13.5	2187	2436	-10.3 %	146	7.7	281	46	54	75
	+5.0	150	13.4	2013	2365	-14.9 %	142	7.5	279	47	53	74
ALC 0%	-5.0	203	15.6	3153	3095	1.9 %	185	9.3	295	54	46	85
	-2.5	194	15.5	3007	2954	0.8 %	179	9.2	287	53	47	85
	0	**186**	**15.7**	**2913**	**2921**	**-0.3 %**	**175**	**8.8**	**294**	**54**	**46**	**84**
	+2.5	172	14.8	2546	2706	-6.0 %	162	8.2	292	53	48	82
	+5.0	163	14.9	2421	2693	-10.1 %	161	8.2	291	53	47	82
ALC +15%	***-5.0***	***206***	***17.4***	***3590***	***3435***	***4.5 %***	***206***	***10.0***	***304***	***61***	***39***	***92***
	-2.5	200	17.0	3400	3243	4.8 %	194	9.6	299	61	39	92
	0	191	16.9	3219	3217	0.1 %	193	9.2	310	59	41	90
	+2.5	183	16.9	3093	3126	-1.1 %	187	9.0	308	61	39	90
	+5.0	174	16.5	2866	2970	-3.5 %	178	8.7	302	59	41	88
ALC +30%	-5.0	210	19.3	4053	3705	9.4 %	222	9.9	332	69	31	93
	-2.5	206	19.0	3914	3511	10.5 %	212	9.8	320	69	31	94
	0	196	18.7	3658	3514	4.1 %	210	9.2	338	68	32	89
	+2.5	192	18.6	3571	3347	6.2 %	201	9.2	324	68	32	90
	+5.0	183	18.4	3365	3264	3.1 %	195	8.8	329	67	33	86

3 Theoretical Framework

This section of the literation review is to give a brief description of various conventional welding process and the CMT process in Cladding and Additive manufacturing which is the basic interest for this thesis.

3.1 Welding Processes

The different kind of welding processes such as laser light, laser welding, Gas tungsten arc welding (GTAW), Gas metal arc welding (GMAW), typical hardfacing materials, Cold Metal Transfer (CMT)

3.1.1 Laser light

The term laser is an acronym of light amplification that is stimulated by emission of radiation. This term was first used by Gordon Gould 1959, on a conference paper described as 'The Laser, Light Amplification by Stimulated Emission Radiation'. The first functional laser was used one year afterwards by Theodore H. Maim an at the Hughes research laboratory on Malibu California. Rudby laser and a pulsed laser on 649nm wavelength was used (Buchfink, 2007). The same year the first continuous wave laser was operated by William R. Bennet, Ally Javan and Donald herriott which worked in the infrared spectrum. At the second half of the 20^{th} century and the beginning 21^{th} century, the laser power and its reliability increase considerably whilst its cost reduced. This encourages the use of lasers in many industries as cutting and welding heat treating etc.

The light which is produced from laser source can be classified as monochromatic, coherent and directional. It is monochromatic due to the narrow electromagnetic spectrum of the beam, it is coherent due to all photons produced are in phase and directional due to travel direction of the produced photons

The basic concept of Laser system is:

- Laser pumping Energy
- Active medium
- Mirror (Fully and partially reflective)
- Laser beam

The general laser process is represented in Figure 3.

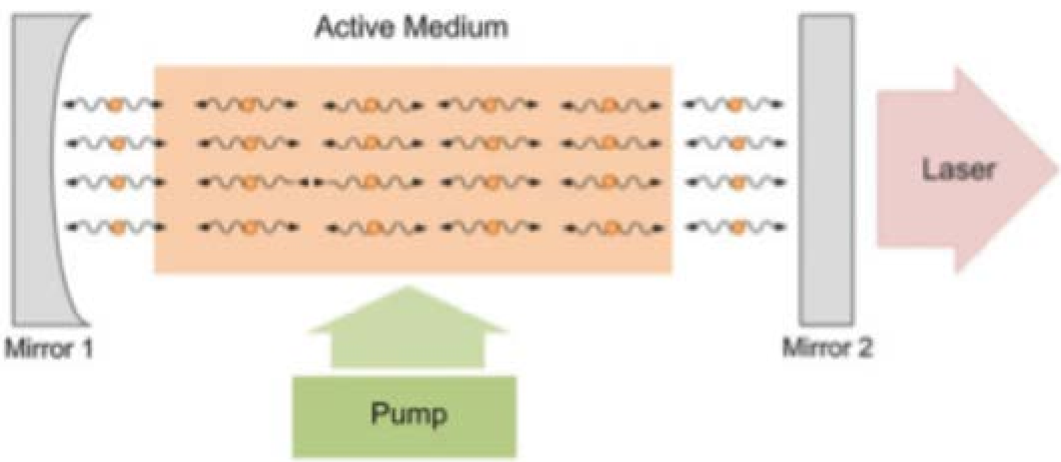


Figure 3 : Laser schematic representation, adapted from Rodrigues Pardal (2016).

3.1.2 Laser Welding

Among the most important innovation in the modern times is laser (light amplification by stimulated emission of radiation). This equipment is widely across all industries and it is applied in producing coatings. The idea of LSC is that a new layer of material (metallic, composite) is fused onto the surface of the material by using a coherent and high laser beam irradiation. The laser beam is created by producing energy in the form of light or energy into a system. The electron in the medium become excited and begin the transfer energy in the form of photons. Thereafter, the electromagnetic energy created is focused into the surface of the material. Also, the energy absorbed by the material turns into heat through the interaction between atoms in the lattice. The interaction creates vibration that creates localized heat energy. However, this causes melting and/ or evaporating in the material which creates a melt pool (Quazi et al., 2016).

The key laser welding equipment is high power laser that includes solid laser and gas laser. Solid is the Nd: YAG laser. Nd is the rare-earth element and YAG represent yttrium Aluminum Garnet that has similar crystal structure as ruby. Gas laser is the so-called CO_2, its working medium is molecular gas, which can work continuously and output very high power, in which the standard laser power is between 2-5KW (Linkedin, 2015). However, the substantive difference between different type of lasers is the wavelength of the light produced (CO_2: 10,6µm; Nd – YAG: 1,06 µm; diode: 0,8-1,0 µm) (Apple, 2015). However, there are some limit of laser welding application:

1) ''It requires high assembly accuracy for weldment and it should have no obvious deviation of beam on work pieces. It is because that the flare is too small and the welding line is too narrow. If the assembly accuracy and beam position cannot meet the requirements, it is easy to make weld defect. 2). The cost and initial investment on laser and the relevant systems are high'' (Apple, 2015). The schematic of laser welding is represented in Figure 4.

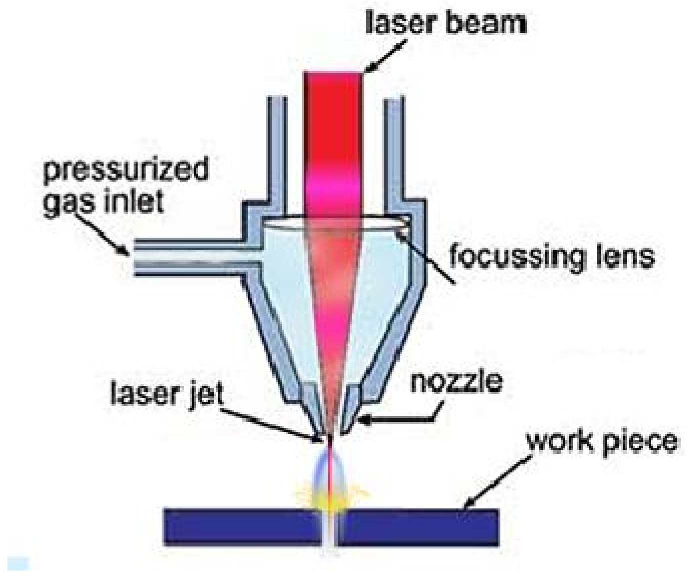


Figure 4 : Schematic of Laser Welding, adapted from Apple (2015).

Lastly, the way the laser interact with the material can be described in two perspectives:(Rodrigues Pardal, 2016)

- System parameters, these are the parameters that are available to the laser user (power, spot diameter and travel speed). The parameter dismisses the interaction between the laser and the material and how energy is transferred to the workpiece.
- Fundamental material interaction parameters, this perspective tries to verify how the material is affected by the laser light and considers the interaction between the laser and the material, by producing useful meaningful physical parameters.

3.1.3 Gas Tungsten Arc Welding – GTAW

GTAW (Gas Tungsten Arc Welding) was developed in the middle of XX century due to the inability of the common welding process to shield nonferrous metals as Al or Mg. During the 2nd world war there was need to build aircraft with lighter nonferrous alloys. With the availability of tungsten electrode and a direct current source power with negative electrode, efficient and stable heat source was produced to make excellent welds. GTAW uses a non -consumable tungsten wire to initiate the ignition in the presence of inert gas (Helium and argon) atmosphere. The electric arc is to provide the heat for the welding pool and if necessary melt the feed wire in the welding pool. Consumable wire is being fed manually or automatically while the welding arc is always made between the tungsten electrode and the substrate. At the time the welding arc and pool are stable, the torch is moved along the joint to melt and make weld. Figure 5 is the schematic of the GTAW welding process.

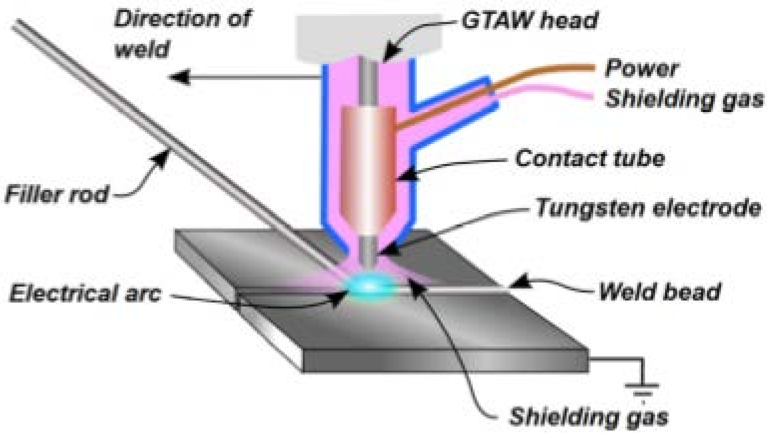


Figure 5 - GTAW process welding schematic, adapted Rodrigues Pardal (2016).

3.1.4 Gas Metal Arc Welding – GMAW

Gas metal arc welding (GMAW) also came into existence at the beginning of 20th century, 1920. During 1948 the first commercially available system was produce, which was tag as a high current density with just metal electrode used, using an inert shielding gas. Just as GTAW, this process was also used to weld aluminum. GMAW is one of the most industrial welding technique use due to its development regimes from low density current, the used of active gas as the shielding gas and also its application in different metals.

GMAW is a welding process that uses the welding arc between the consumable electrode and the substrate to generate heat to form a weld pool and transfer the electrode to the substrate. This process is usually shielded by an active or inert gas in which the electrode is continuously consumed and transfer to the work piece. Figure 6 is the schematic of the GMAW welding process.

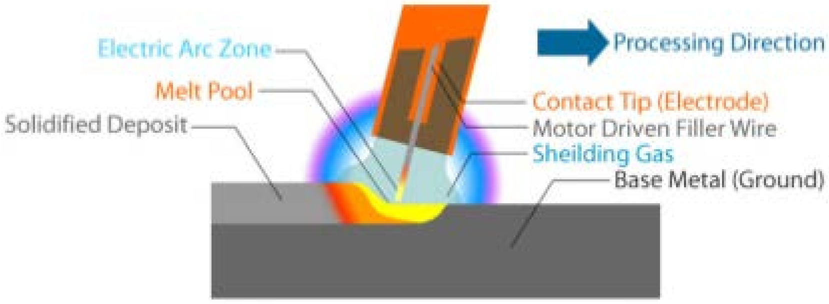


Figure 6 – GMAW welding schematic, adapted from Rodrigues Pardal (2016).

GMAW has different kind of transfer modes this depends on the objectives for a particular welding procedure and the kind of metal. These modes can be described as metal transfer mechanism and can be described as the way in which the molten electrode is deposited on the work piece.

- Short Circuiting transfer
- Globular transfer
- Spray transfer
- Short Circuiting Transfer

This transfer mode is actualized when using low current level and small electrodes diameter. The transfer mode does not happen in the welding arc; it occurs when the electrode is in contact with the work pool. There are different electrical stages during short-circuit transfer cycle. At first the electrode starts to melt and formed a weld pool, due to forward motion of the electrode it get contact with the weld pool. At the point the current increase and the temperature of the electrode increases and a detachment of the electrode metal is achieved. The metal is then added to the molted pool and a new area is ignited between the electrode and the work piece. This arc is enough to keep the weld pool in a liquid state. After which a new short circuit is formed and a new cycle is initiated. Because of the low current and the heat input this process is used for welding thin metal and root pass. Figure 7 represent the GMAW short circuiting transfer mode arcing phases.

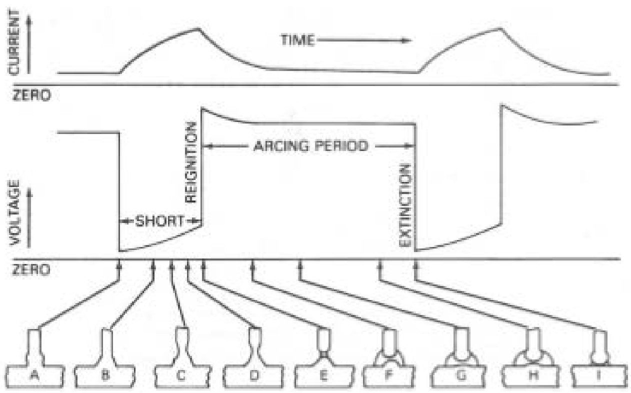


Figure 7 – GMAW short circuiting transfer mode arcing phases, adapted from Rodrigues Pardal (2016).

- **Globular Transfer**

Globular transfer mode is characterized by an electrode detachment with a large radius than the electrode diameter. This transfer occurs for a relatively low current using reverse polarity regardless of the shielding gas used. For shielding gas like Helium and carbon dioxide this can be applied with usable levels of current. For average currents, slightly higher than short circuiting transfer it is possible to have globular transfer. Though, for low arc length (low voltage), the high dimension droplet can short circuit and form spatter. That means the arc length needs to be long enough to allow detachment avoiding short circuit.

- **Spray Transfer**

Spray transfer mode occurs mostly in Argon rich atmosphere shielding and it is characterized as spatter free metal transfer. This mode is used for reversed current mode, for current higher than the transition current, for lower current it is expected to have globular transfer. The droplets formed are small and they are accelerated by an arc forces. Smaller dimensions of current prevent the occurrence of short circuit. This welding transfer mode is difficult to apply on thin substrate due to high heat input and distortion and the high arc force which can penetrate through the thin substrate.

3.1.5 Typical Hardfacing Materials

Basically, the selection of better hardfacing (coating) material depends on the application and the environment. Making correct material selection the lifetime of components can be increase greatly. Table 3 highlight some common steels, steel alloys and Ni- and Co-base alloys and their properties as hardfacing. When resistance to abrasive wear is needed different carbides (Cr, W, V or B) in an iron, cobalt or nickel matrix are used. Work hardening alloys with austenitic structure (e.g. austenitic manganese steel) are applied when the impact resistance is the property that need enhancement(DEARNLEY, 1988)

Table 3 – Hardfacing materials and properties, adapted from DEARNLEY (1988)

Material type	Properties of deposits	Type of duty for which deposits are most appropriate
Austenitic manganese steels	Tough, crack resistant and soft. Ability to work harden	High stress, heavy impact
Martensitic and high speed steels	Good combination of abrasion and impact resistance. Abrasion resistance increases with carbon and chromium content at expense of impact resistance.	Non-lubricated metal-to-metal wear.
Nickel- and cobalt-base alloys	Wear, corrosion and heat resistant, with good all round strength but low ductility.	Abrasive conditions accompanied by high temperature and/or corrosion.
Martensitic and high chromium irons	Excellent resistance to wear by most minerals. Brittle.	Highly abrasive conditions.
Tungsten carbide composites	Extreme resistance to sliding abrasion by hard minerals. Worn surfaces become rough.	Extremely abrasive conditions where extra cost is warranted.

Increasing abrasion resistance ↓ ; Decreasing toughness ↑

When selecting hardfacing materials heat and corrosion resistance plays vital aspect. Cobalt and nickel-based alloys are considered to have a great resistance to heat and corrosion whilst martensitic alloy steels and manganese steels is fast to corrode under corrosive environments. Figure 8 depicts relative wear, impact, heat and corrosion resistance of different materials and hardfacing.

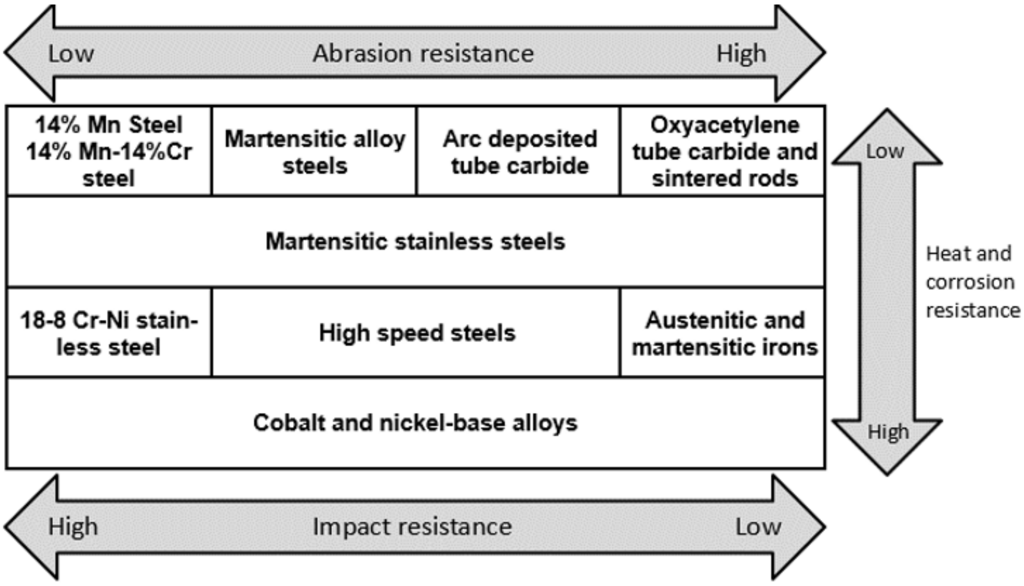


Figure 8 – Relative abrasion, impact, heat and corrosion resistance of hardfacing alloys, adapted from DEARNLEY (1988).

3.1.5.1 Overlay Welding of Stellite coatings

In this section, stellite coating by various welding process, mostly GMAW-processes and some other reports with TIG – welded overlays are discussed and summarized.

Fouilland et al. (2009) studied the friction behavior of MIG- welded stellite 21 hardfacing with friction-induce work-hardening (FIWH) of the multilayer coatings produced. The coating was deposited using shielding gas with (GSAW) on a hot-working steel 55NiCrMoV& as the base material (Preheated to 400 ^oC). The filler material used was flux cored stellite 21 wire with 1.6 mm diameter. The hardfacing were produced in four layer with argon as the shielding gas. Different type of welding program was used such as P1 and P2 with semi-automatic (S.A.) and full automatic process control. The P1 program with less energy, achieved a dilution level of approximately 7.7% (S.A) and 16% (A) with the first deposit layer, whilst P2 program results in a higher dilution levels of 37%(A) and 40% (S.A.) in the first layer. The highest FIWH rates was achieved with the lowest dilution top layers. This observation probably leads to increase in wear resistance of the coatings.

Reviewing this other study by Fouilland et al. (2007) on microstructural variation in Co-based superalloy caused by welding process energy. The process and materials are the same as in Fouilland et al. (2009) with similar dilution rates. The chemical analysis shows that eutectic precipitates are found between the primary dendrites of a cobalt rich FCC phase and micro hardness levels of 350-400 HV0.2 were reached. Cored dendrites with high content of Mo and Cr at their surfaces are formed during solidification with low and high welding energies. It was perceived that welding energy has greater influence during secondary precipitation that occurs in the deposition of successive layers as it requires high temperatures for sufficient amount of time. It can be observed that within the dendrites around the eutectic precipitates reach in MO and Cr precipitated and fine cuboid-shaped particles of $Cr_{23}C_6$ is seen. P2- welding program with higher welding energy produced coarse size precipitates. It was concluded that the presence and the size of $Cr23C6_{carbides}$ affects the micro hardness levels.

Shanmugam and Murugan (2006) studied the effect of process parameters using in cladding of valve seat ring with Stellite 6 alloy using GTAW. GTAW was selected because of its advantages like superior welding quality, low equipment cost and high accuracy. Stellite 6 has a great resistance to corrosion and erosion even at higher temperatures. Stellite 6 rod of diameter 3.15mm was used with argon as shielding gas. They try to optimize the process parameters to achieve good welding properties like dilution and weld bead width. 20 test was conducted and they achieved a dilution rate of 6% to 17.5%. The penetration into the base material varied from 0.17mm to 0.37mm. Which implies that dilution is very limited with TIG.

3.2 CMT – Cold Metal Transfer

CMT has a long history, fronius began the possibility of arc welding of steel and aluminum in 1991, it became obvious that the possibility is by reducing the heat inputs (Lorenzin and Rutili, 2009). Furthermore, the idea came from a customer that needs optimized welding solution with a few drops of molten metal on some extremely thin sheet. In 2002, the idea became obvious and well-studied, which the developmental work for an optimized solution for industrial work began in intensely.

This process mostly works in short circuit (dip transfer) transfer mode which is defined by low current and voltage which signifies low heat input. The important difference of CMT from the conventional GMAW is the full digital control of the welding process. The microcontroller controls the feeding of the wire for the CMT process through the feed motors, no longer dependent on the electrical characteristics. An initial high pulse of current is formed which formed an arc between the advancing electrode and the substrate that melt the electrode tip. The current is reduced following the pulse, as soon as a short circuit is indicated, the voltage reduces, the current is further reducing to a low background value and the wire is retracted, which leads to detachment of the molten droplet. Thus, this process is named CMT due to the metal transfer takes place when the current is very low. Figure 9 shows the different CMT phases. Different researchers carried out various research with CMT process, below is the literature review from their research.

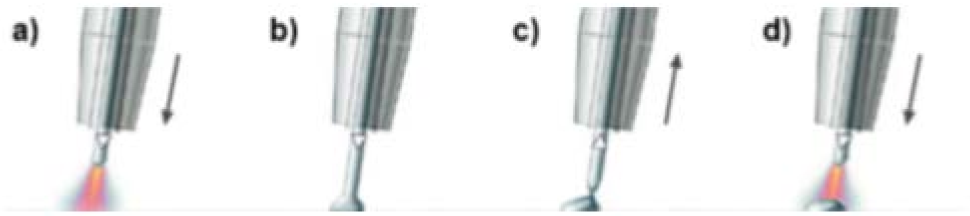


Figure 9 – Different CMT phases, a) arc ignition b) Short circuit phase c) inversion of wire feed direction d) arc re – ignition, adapted from Rodrigues Pardal (2016).

Several studies have been carried out to investigate CMT process, see examples as follows. Zhang et al. (2009) studied the principles, equipment, operation details, advantages, application and limits of CMT processes. However, reports of welding Aluminum alloys has shown that using CMT process is okay for thin sheets owing to its low heat input. Moreover, this low heat input also result in decrease in deformation and residual stresses. Additionally, low spatter and gap bridging quality in this process was also reported (Ahmad and Bakar, 2011, Feng et al., 2009, Zhang et al., 2009). The process saves a lot of energy, because it provides only the energy needed for the process. The CMT process was also used in joining of dissimilar metals such as joining of aluminum alloy to galvanized steel, where the joining is done by brazing of Aluminum alloy onto steel (Cao et al., 2013c, Feng et al., 2009, Lin et al., 2013). CMT was also reported using copper-based ($CuSi_3$)(Shang et al., 2012) and also 4047 aluminum alloy filler wires (Cao et al., 2013b) for joining of Aluminum and magnesium. When weight reduction is of great concern, the CMT process is recommended for automobile joining application. CMT process was also studied for the joining of titanium to aluminum alloys and also to copper alloys, the application of this process is centered towards the aerospace and medical sectors (Cao et al., 2014, Cao et al., 2013a) . However, much report is not available using CMT process as surface coating techniques, with the fact that this technique is quite new. Lorenzin and Rutili (2009) reported that CMT process can probably be used for anti-corrosive coating applications. Thus, in the aforementioned research, a feasibility study was carried out for the depositing of Inconel 625 alloy on the surface of carbon manganese steel. Thereafter, comparing the CMT process with the conventional pulse-arc mode and pulse hybrid mode with respect to dilution and deposition rate. Rutili (2009) concluded that pure CMT shows lower dilution and high deposition rate. Pickin et al. (2011) studied CMT for a low dilution cladding application. However, it was discovered that the CMT short circuit mode appear in lower parameter range, there was a change of the combination of both spray and short circuit mode from the middle to upper data range. Thereafter, they analyze the low dilution cladding for ternary aluminum alloy (Al-Cu-Mg) with binary aluminum alloy filler wires. This ternary aluminum alloy is known to be susceptible to a hot-cracking problem when welded with binary aluminum filler wires.

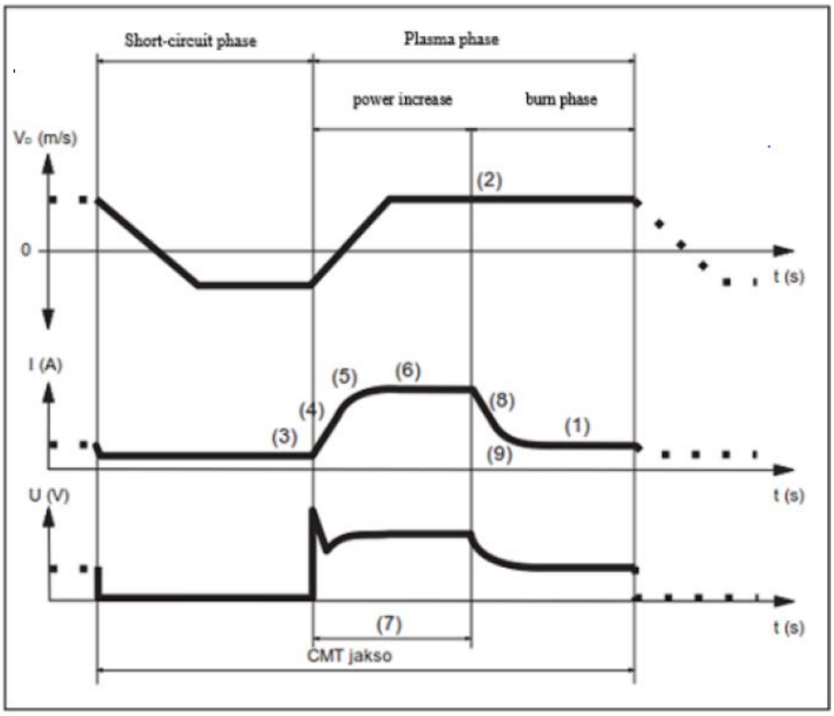


Figure 10 – Wire feed rate, current and Voltage curve during a CMT cycle, adapted from Fronius (2017b)

Moreover, the CMT process was used for cladding ternary aluminum alloy with binary alloy, which is then welded with conventional techniques, that probably reduces the chances of hot cracking. Ola and Doern (2014) studied cladding process for nickel super alloy, they reported a positive result of defect free and perfectly bonded clads and recommended the process for repair of nickel base super alloy parts in gas turbine. However, no much report for overlay coating of Aluminum is available. Rajeev et al. (2014) studied CMT technique for coating of aluminium with AL-Sn-Mn alloy and they concluded that the bead angle and deposition rate are nonlinear functions of the welding speed and that CMT process is discover to be a low energy process for weld and repair of Al-alloy component.

One the main objective of this thesis is to examine the over layer coating of stainless steel with different filler wire using CMT-laser process. Figure 10 are the characteristic curve for CMT-process. The top of the curve shows the wire feed rate. The back and forth motion can be seen in the curve during the short circuit phase. The numbers in the figure indicate multiple variable that can be adjusted to improve the welding process. Which are power and current adjustments and the lengths of each phase in the cycle.

CMT – process is an inclusive type of welding method that can be used among different type of applications, also cladding because of the low heat input.

3.2.1 CMT Pulse

''The CMT pulse process is a combination of pulse cycles with CMT cycles, increased heat input, welding speed, specific and variable addition of pulses and widespread performance and flexibility''(Fronius, 2017a). However, at the first phase the wire is retracted and the arc is being positive like the normal CMT process. Thereafter, comes the CMT pulse phase where the wire is moved towards the work piece and the droplet is detached simultaneously. The arc is extinguished at this point and a normal CMT process continues. This process is represented in Figure 11.

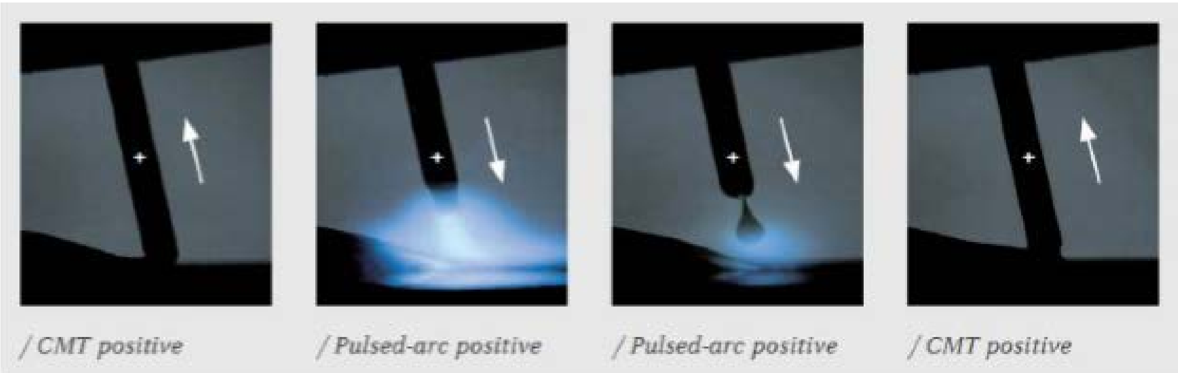


Figure 11: CMT pulse cycle (Fronius, 2017a).

Figure 12 highlight the characteristic curves for CMT pulse cycle. The pulses are seen in between the CMT cycles, for this system there are two pulses. The number of CMT cycles and can be selected between 0-500 (Tapiola, 2017).

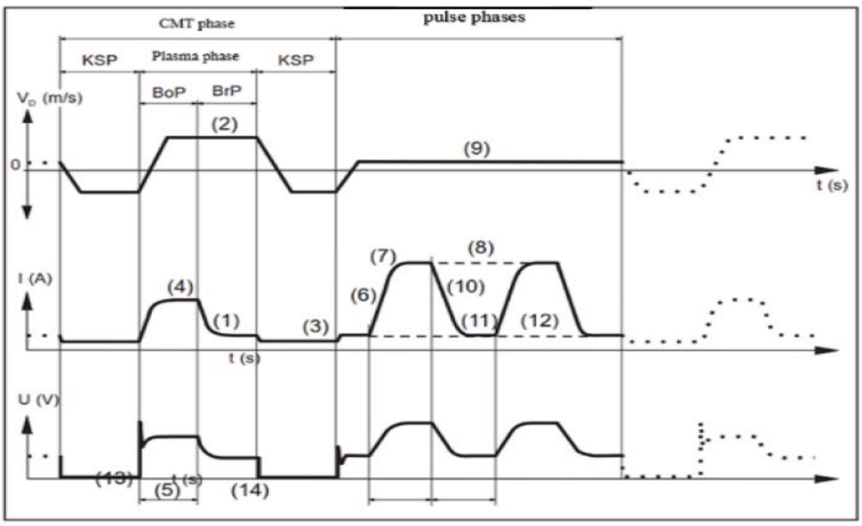


Figure 12 : Wire speed rate, current and voltage curves during a CMT pulse cycle. KSP= short circuit phase, BOP= power ramping phase, BP= Burning Phase, adapted from Tapiola (2017)

CMT pulse welding gives a narrow bead and it is mainly used in welding of aluminium. For cladding process, it is not recommended as the heat input is high which affect the dilution and the composition of the coating. It allows higher welding speed with the increase heat input.

3.2.2 CMT Advanced

The recent development in CMT technology is the CMT advanced, the principle of this variant is shown in Figure 13. *However, ‘’Polarity of the welding current is incorporated into the process control, polarity reversal takes place in the short circuit phase, allows a more precisely control heat input and a high gap bridging – ability due to increased deposition rate’’ (Fronius, 2017a).* The process flows with the positive and negative CMT cycles and combines these two, to introduce alternative current AC into the process. Which makes the process even cooler than the normal CMT process.

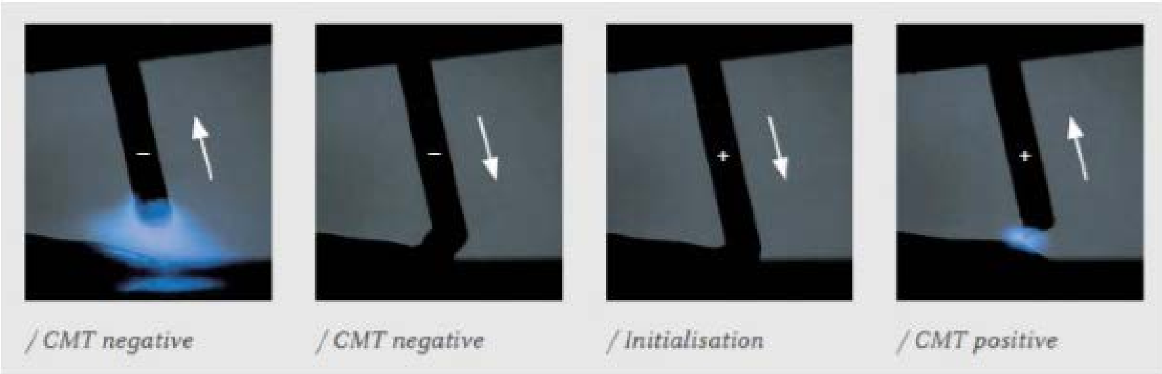


Figure 13 – CMT Advance cycle, adapted from Tapiola (2017)

As can be seen in Figure 14 below as the polarity of the cycle changes after normal CMT phase in the CMT advanced process.

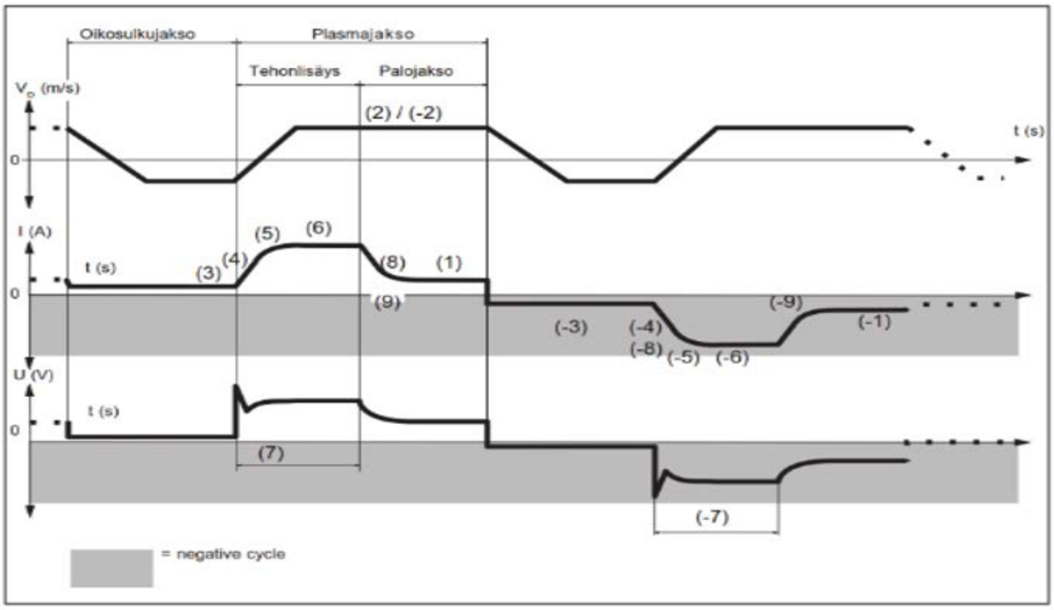


Figure 14 – Wire sped rate, current and voltage curves during CMT Advanced cycle, adapted from Tapiola (2017).

CMT Advanced allows the use of higher WFR values, and because the droplet produced by the negative cycle are larger, higher deposition rates are achieved.

3.2.3 CMT Pulse Advance

''CMT pulse advance is a combination of electrode negative CMT and electrode positive pulsed arc cycles, produces absolute precision, greatest mastery of the arc'' (Fronius, 2017a). The combination is represented in Figure 15. The first stage is the CMT negative phase in which the wire moves towards the work piece. Follows by an initialization phase where the wire is retracted and the cycle is positively poled, that proceed to a positively poled pulsed-arc cycles.

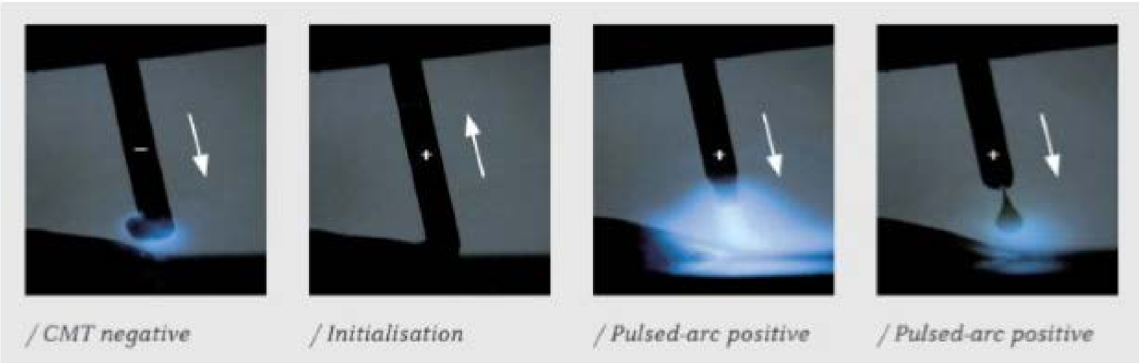


Figure 15 – CMT Pulse Advanced cycle, adapted from Tapiola (2017)

From Figure 16 below, it is seen that only the CMT phases is negatively poled, the pulses are positively poled in the CMT pulse. The pole difference is the only thing differentiating the CMT pulse from the CMT pulse advanced process. CMT pulse advanced is designed to fix bridge-gaping.

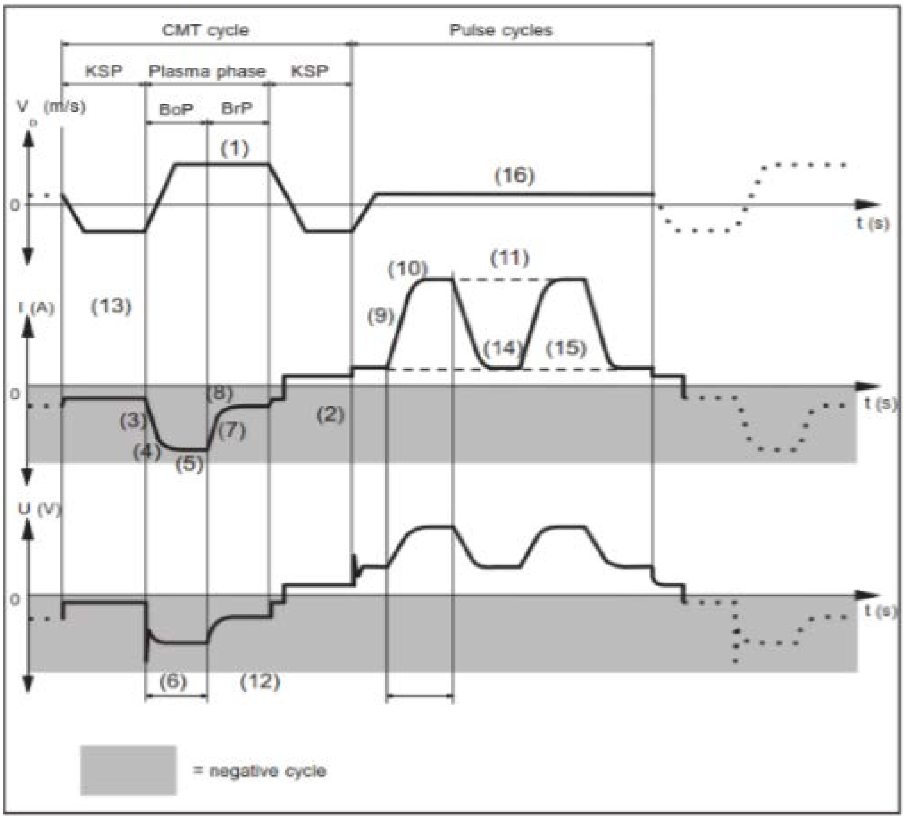


Figure 16 – Wire rate, Current and Voltage curves during CMT Pulse Advanced cycle. KSP- short circuit phase, BoP- power ramping phase, BrP – burning phase, adapted from Tapiola (2017)

3.2.4 CMT Dynamic

CMT dynamic is the most recent development in CMT process. It is mainly designed to tackle the challenges while welding thicker plated. The to- and fro- wire movement has been increased to 130Hz which raises the operating limit of the process. The increase of the wire motion enables higher welding speed, wire feed rate and increasing deposition rate that promotes deeper penetration. CMT Dynamic has more heat input, increase arc input and more energy. The main reason is that is not design for cladding (Tapiola, 2017).

The different arc mode and their differences can be seen from Figure 17 in which arc current and voltage has been collected. Cong et al. (2015) uses an AA2319 wire consumable on a wrought AA2219 alloy plates. The shielding gas used was Argon.

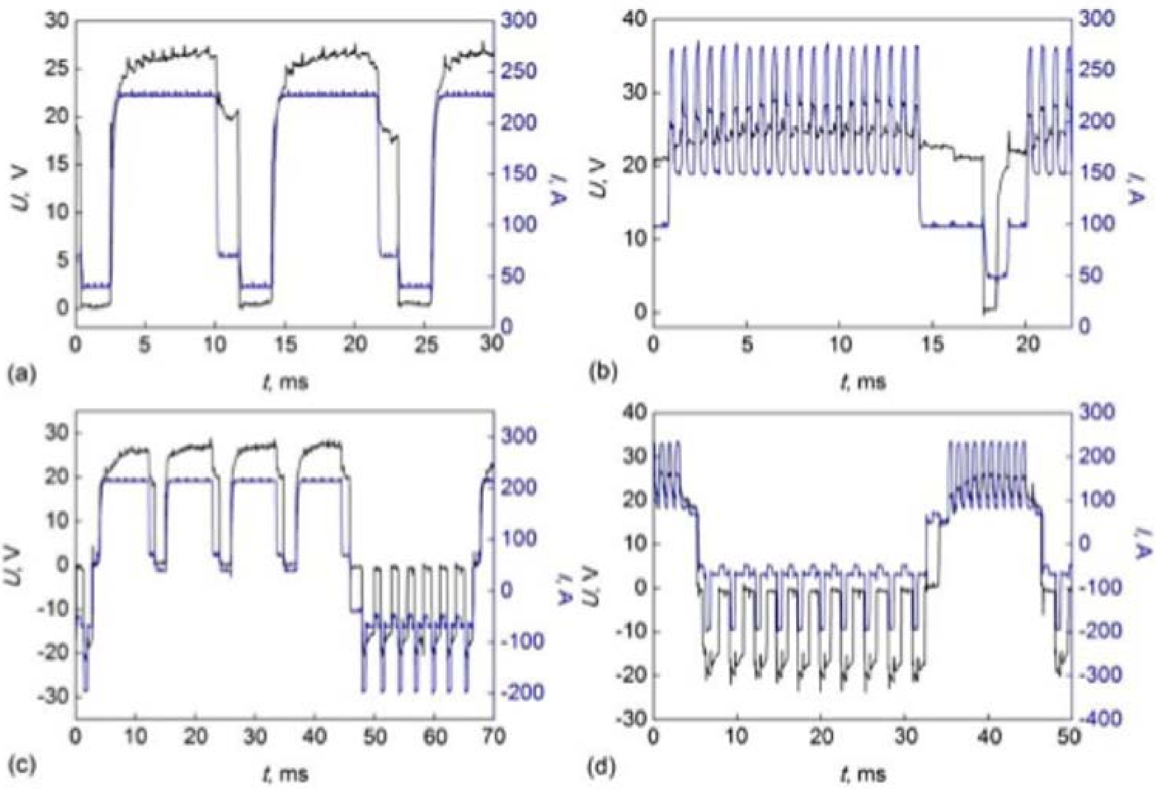


Figure 17 – Comparison of different CMT- alternatives; (a) CMT, (b) CMT Pulse, (c) CMT Advanced, (d) CMT Pulse Advanced (WFS - 7,5 m/min) adapted from Cong et al. (2015)

3.3 The Use of CMT process in Cladding

Over the years, CMT process has been applied for cladding of Ni – base super alloys and Al alloys. However, depending on the process parameters and the materials in question, CMT reaches a maximum deposition rate up to 5.5-6 kg/h with single wire unit. This value is comparable to some similar overlay cladding method. Lorenzin and Rutili (2009) mentioned that the dilution and penetration of the process can probably be controlled by changing the synergic line and adjusting the corrections parameters.

Thereafter, Lorenzin and Rutili (2009) investigated using Inconel 625 alloy (1.2 mm diameter wire) surface facing on sections of carbon – manganese steel sheeting that is commonly used in structural applications. The CMT pulse, classic pulsed arc and CMT Arc welding processes was used. They used weld speed of 250mm/min, 10mm oscillation movement, argon as the protective gas and a stickout of 20mm. They concluded that all the test produce solid, defect free coatings. From all the test (that is label as test 1-3) they concluded that pure CMT produced the less diluted coating which implies the lowest presence of iron derived from dilution. Test 3 which is pure CMT, is the most promising high deposition rate of 5.6kg/h and mean facing height of 4.2mm and the maximum iron content reach a depth of 2.5mm is equal to 2.7%. Moreover, Inconel 625 wire has iron content of 1-1.7%, meaning that by dilution, the facing process has contributed to the surface more than 1% to the surface that is advantageous. In contrast, the Purse – Arc (Non CMT) method had an iron content of 13-14%. Increasing dilution seems to affects the chemical composition of the coating and having a negative effect on the hardness value, corrosion and wear properties. Low dilution implies a low heat input that is beneficial to the possible change in the microstructure and geometrical distortion.

Additionally, Ola and Doern (2014) studied the repair CMT- cladding of Inconel 718 super alloy with a 0.89mm Inconel 718 wire. The microstructural characteristic and the geometry of the clad was investigated. They used Argon as the shielding gas, a contact tip-to-work piece with different push angles, welding speed and wire feed rate. The CMT process was found suitable for the repair of Inconel because of defect and crack free clads were obtained with low dilution. Secondly, calculation of heat input for different welding wire feed speed used. As can be seen from Figure 18 a linear relationship between the heat input and the wire feed speed was obtained. Further calculations and statistical analysis was implemented to develop a regression models. This model proves to be probably accurate in predicting the width, depth and weld metal dilution ratio of the clads. It helps in optimizing the welding process parameters. Finally, they concluded that a contact angle of the weld bead greater than 115^{o} assist for overlapping of welding bead when adding a multiple successive pass.

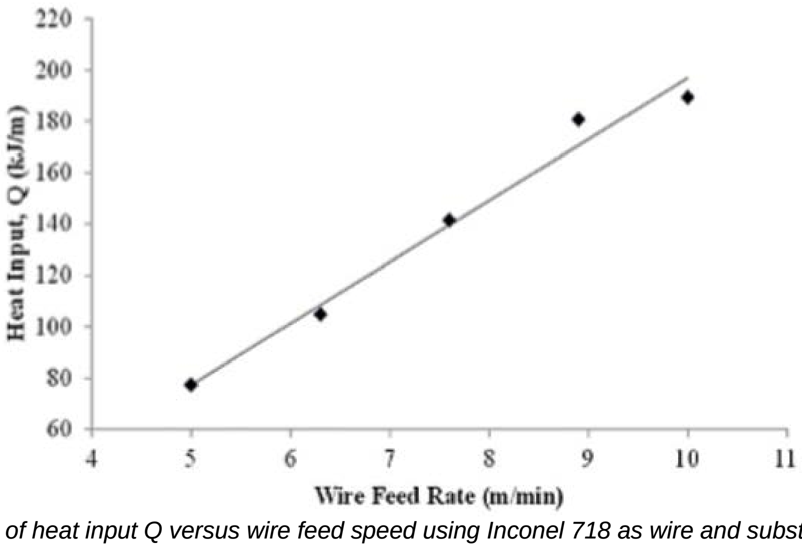


Figure 18 A plot of heat input Q versus wire feed speed using Inconel 718 as wire and substrate adapted from Ola and Doern (2014)

In addition, Pickin et al. (2011) study the use of CMT in low dilution cladding of Al alloy 2024 with Al-2139 filler wire. This particle alloy has the tendency of solidification cracking, CMT could identify this challenge and provide solution. However, they were able to control dilution quite well comparable to pulsed MIG welding normally used in this application. Additionally, Rajeev et al. (2014) carried out a test on commercially pure 3mm thick Aluminium plate that was cladded with an Al-Si-Mn filler. They observed a low dilution and pore free coatings with significant increased hardness compared to bulk material. They used Argon gas as the shielding gas and the process was carried out with different weld speed to study the effect on weld dilution, geometry and characteristics. They probably concluded CMT to be okay, with low energy process for weld repair of aluminium alloy components and produced a thick coating even with a single pass.

Horever, Rozmus-Górnikowska et al. (2014) look at coating of ferritic – perlitic steel substrate coating with Inconel 625. The requirement for Nickel base coating is an iron content below 5wt%. The Inconel 625 filler material has an iron content of about 0.3wt%, and the applied coating has an iron content of 2-3% which shows a low dilution, the coating is also defect free. Zhang et al. (2015) studied the effect of welding speed on microstructures on AZ31 magnesium alloy clad. AL-4043 synergic program was used. The base material and the filler material were of the same nominal composition. They discovered that a welding speed of 10-12mm/s produced the best quality coating because of the effects of welding speed on cooling rates and heat input values. It implies that higher cooling rate gives precipitate less time to nucleate and grows that lead to less precipitate. Higher heat input result in narrower HAZ area.

Additionally, Dutra et al. (2016) studied Inconel 625 coatings that was cladded by MIG/MAG pulsed + DC, Pulsed AC and CMT process with steel plate as the substrate material using 45^o welding position. The coating process was carried out starting from the bottom and moving upward. A weaving motion was used and the wire electrode (1.0mm in diameter) was used for each process. However, Pulsed +DC gives the highest average power, 4127W, and the dilution was at 28%. Moreover, the CMT process which is the coldest process has a dilution of 3% that is low and fusion might not be adequate. The AC-version had a dilution of 8% and this result was the best in terms of runoff and quality of coating. Probably the welding power of CMT was not high enough to produce a good quality cladding, the weld beads remained quite narrow and not enough wettability.

Lastly, Liang et al. (2017) studied CMT/TIG hybrid cladding of 6061 aluminium alloy. This hybrid process was carried out in such a way that the arcs are not interacting with each other. Both torch was perpendicular to the weldment and the TIG-torch was clamped in front of the CMT-torch to the welding direction. It was observed that the addition of TIG promote the wettability of the molten metal and contribute multi - passes and cladding of aluminium alloy. TIG plays an important role in preheating of the base material which have a great influence on the contact angle and dilution of the weld bead by increasing the value of both.

3.4 Synergic Lines

Due to customer's demand fronius design different synergy line for different filler materials and filler diameters. Synergy lines are probably the most important part in CMT welding process because they provide the basic parameters automatically to each filler material and in theory, an accurate program should enable the manufacturer a good quality welds. However, for robotic welding, there are number of welding parameters controlled by the robot and this need to be adjust to give a good result. Synergic lines containing database need to be uploaded into the remote control from computer and selected prior to welding. There are also other type CMT- equipment with less automation and additivity apart from the equipment with synergic lines. Moreover, the user needs to adjust the voltage in addition to wire feed rate. Because of the design of the system, the amount of synergy line is limited.

Synergy lines are design with the help of an oscilloscope and a high-speed camera to optimize the process and to examine the different characteristics in more detail. The idea of creating a new synergy line begins with a low value of wire feed rate (WFR), and with that value a functional voltage region is defined with the help of the equipment mentioned. However, the process is repeated for each WFR-value until the maximum is reached.

Figure 19 depicts effects of Arc Length correction are presented. ALC is used to fit the voltage of each WFR-value selected from -30% to +30%. Which gives the working area of each synergic line marked with yellow color (Gmb, 2013).

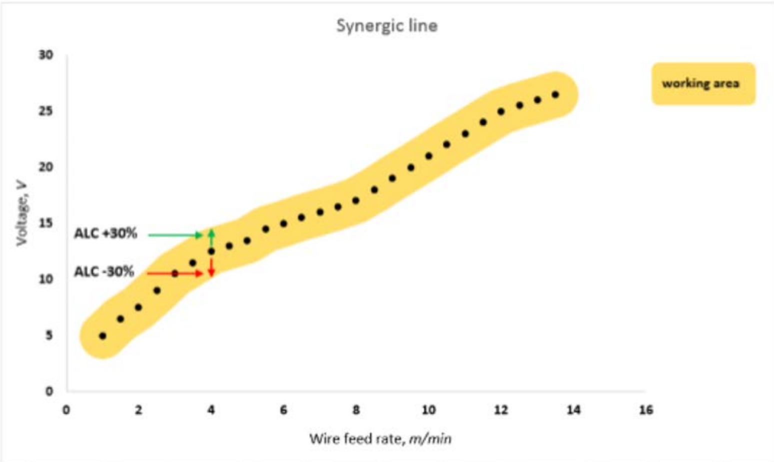


Figure 19: An illustration of a synergic line

These synergic lines can be alter using the RCU – controller by adding characteristic points. These modifications can be used for example to increase the maximum ALC value of a specify WFR- value to achieved a higher voltage. This requires more training and knowledge of the system, it sometimes not recommended or necessary.

3.4.1 CMT – Process Correction Parameters

Though choosing the right synergy line for the right material will give an accurate result, some of the parameters need to be adjusted to get an optimal result. Arc Length Correction (ALC), is used in setting the spatial elongation of the arc plasma column. Shorter arc has a favorable effect on welding speed and against undercuts, and a long arc has positive effects in terms of wide weld seam and edge formation. For traditional process ALC controls the voltage and WFR, but it is more complex for CMT process (Gmb, 2013).

ALC value can be adjusted from -30% to +30%. When reducing the arc length, the wire return time decreases and the process frequency increases. The negative value of ALC increases the forward acceleration of the wire, also decreases heat input and average voltage. The droplet becomes smaller and the amount increases. Due to increase of the arc length the return time increases and process frequency decreases. However, meaning smaller amount of bigger droplets. Longer arc losses more energy than a shorter arc, this affect the energy of the process (Gmb, 2013). For ALC value of +30% the arc the wire forward speed during the arcing phase is set at 18m/min and with ALC of -30% the value is set to 30m/min. Altering of the ALC also affect the arcing-short-circuiting ratio and frequency. Pickin et al. (2011) find out that adjusting ALC value from +10% to -30% results in change of short circuit duration from approximately 5ms to 10ms respectively. The effect of ALC value can be seen in parameter 2 in Figure 19.

One other important correction factor is called dynamic correction (DC). This correction simulates inductance and it is used to adjust the duration and properties of short circuit break. Moreover, DC controls the controls arc pressure by controlling the reignition current. By reduction of the arc force dynamic correction produces a higher reignition current and so a higher arc pressure. For DC, current set to -5 it gives 60% higher current during short circuit. Which makes the droplet explode away from the tip of the wire and more spattering can be observed. Negative value still give more penetration higher contact angle of the weld bead and more stable arc. When DC is set to +5, 60% lesser current is gained as a result of short circuit. Which leads to reduced heat input, lower stability of the arc, less penetration and less spatter. Positive DC is recommended for cladding but this depends greatly on the materials. (Gmb, 2013).

Furthermore, the Stick out of the wire, implies the distance from the contact tip to the weld pool, has effect on the properties of the weld. Changes in stick out in CMT process does not has effect on the stability of the arc, shorter stick out lead to smaller penetration on the base material, decrease deposition rate and produces a flatter weld bead. The basic parameters that can be altered by users for a specific synergy line are: Wire feed speed (WFS), arc length correction (ALC) and dynamic correction (DC). However, this parameter has an impact on the wire speed during the arcing phase when the wire is fed forward towards the melt pool. This speed is larger than the average wire speed. Parameter DC has an effect on the current during the short circuit phase. The parameter ALC and DC has a great influence on the process, welding energy and the resulting weld properties. Just few research has been published on the effect of this parameters on CMT process. Sequeira Almeida (2012) study the effect of ALC and DC on a single bead welding of 1.2mm mild steel with a relatively low weld feed rate of 4m/min. for this research only the value of ALC and DC was varied at a time the other were kept at zero. Thereafter, da Costa Pépe (2010) studied the effect of ALC and DC on 1mm mild steel and type 22-9-4 duplex SS wire Pickin et al. (2011) cladding on plate with 1,2mm aluminum wire.

3.4.2 Wire Feed Speed

The set value of wire feed set controls the power of the welding process according to the synergy line in use. For conventional MAG/MIG welding process the wire feed speed and the voltage is kept constant. The variation of the process parameter like contact tube distance, short circuiting and arcing in dip transfer process, is made by changes in the welding current. Since the wire feed direction in CMT process changes with high frequency depends on the signal to the controller, the actual wire feed speed does not have to be constant, with the set wire feed speed. The parameter ALC and DC also have effect on the wire feed rate. From Almeida studies, it was discovered that the wire feed speed set at 4m/min resulted in actual WFS of 2.75m/min with ALC value of -30% and 3.3m/min for ALC value of +30%. Though, the actual WFS was lower compared to the set value, this is probably as a result of lower travel speed and the wire feed rate was relatively low.

3.4.3 Welding Power

The arc power in arc welding is calculated as (Almeida and Williams, 2010)

$$P_{arc} = I \times V \tag{1}$$

where:

- P_{arc} is the arc power (W),
- I is the average current (A),
- U is average voltage (V).

The heat input on the arc welding is determine as (Almeida and Williams, 2010)

$$E = \eta \times \frac{I \times V}{TS} \tag{2}$$

where E is the welding energy (J/mm), TS is the travel speed during welding η is the effective power, that is usually used in determine the heat input during welding, because some of the heat brought the process is loss by radiation or other loss, not use on heating or melting the wire or base material. 0.8 is usually the process efficiency used for the conventional MAG/MIG. For this project process efficiency η was neglected. The current and voltage reading during welding are usually achieved by recording the average value on the control panel of the welding power source or from the memory of the power source after the welding must have finish. These current and voltage represent average value during the welding. The current and voltage are recorded with high frequency (greater than 1 KHz) data acquisition device (DAQ) and the arc power, current multiply by voltage is determine from each data point during some average instantaneous power that is calculated as: (Almeida and Williams, 2010)

$$AIP = \frac{\sum_i U_i \times I_i}{n} \tag{3}$$

Where:

AIP is instantaneous power, U_i is voltage and I_i is current by each sample acquired by data acquisition system and n is the number of samples.

3.4.4 Shielding Gas

The shielding gas that can be used on MIG/MAG process for welding of nickel alloys include pure Argon (Ar) and mixes of Ar +Helium (He) and Ar + He + CO_2. The gases that contain CO_2 produces a very stable arc and excellent out of position welding characteristic and excellent nickel base to carbon – steel welding characteristics. Due to the present of carbon dioxide the steel surface will be highly oxidized. This oxidized effect can increase the possibility of incomplete fusion on multipass welding, overlay welding. Helium and Nitrogen gas improve the thermal efficiency and improving the wetting behavior of the melt. Argon and hydrogen are often used for tungsten arc welding for improving wetting and flow characteristic of the weld metal. It was observed that welding and using hydrogen gas >1% can lead to loss in weld metal ductility.

The choice of shielding gas in welding of Inconel 625 with MIG/MAG is not too easy, because the short circuiting and spray transfer on MIG/MAG process has a large effect on the phenomenon of the welding, most especially the heat input. From Dutra et al. (2016) research you will find out that on overlay welding with weaving bead using Inconel 625, CMT process require 25% helium in shielding gas compared to pulsed DC and pulsed AC which the wetting was sufficient with Ar +2.5%CO_2. Baixo and Dutra (2011) state that pure argon works only on spray transfer mode.

3.5 Pros and Cons of CMT Cladding

CMT cladding has several benefits. The equipment is inexpensive comparing it to laser cladding, which is probably similar to laser cladding by properties. CMT has a good energy efficiency and the process has the possibility of producing smooth coatings regardless of the material and it is very flexible. The process is a cold process, dilution and penetration can be controlled easily that leads to good coatings properties and composition. CMT has a good deposition rate and achieving a deposition rate of 5kg/h with a single wire. For a twin wire this rate can be doubled. We have different materials available covering a wire diameters varying from 0.8mm to 1.6mm covering both solid and cored wires.

CMT is not as accurate dimensionally compare to for example laser system but rather thin bead can be produced with e.g. thin aluminum wire. However, the coating thickness is rather high. It seems not possible producing a high thickness 1.0-1.5mm thick clad with low dilution and fusion bond. Observing the thickness area, the heat of the process is insufficient which causes defects and lack of fusion.

3.6 The Major Characteristics Distinguishing CMT from the GMWA conventional Welding Process.

The movement of the wire for CMT is integrated with the controller that manages the welding process. Before CMT process the movement of the wire feed was managed by means of predefined fixed or variable movements. For CMT the wire is retracted at the time short circuit occurs. At this point, the wire feed motor inverts the feed direction and the wire is return backwards. At the time the short circuit has ended, and the arc start again, the motor again inverts the direction of the wire feed, which is then push to the piece to be welded, which keep the process stable. Controlling the movement of the motor just like the wire feed speed is not based on predefined times or speeds but instead it is optimized by the microprocessor, so as to maintain and attain the expected arc characteristics. Simplifying this process by means of expression encompassing the operating principle, it shows that the movement of the wire define what happen in the welding bath and what happen in the bath explains the movement of the wire. Thus, this is the reason why it is important to talk of the oscillation of the motor, for instance if the short circuit occur earlier, that means the wire will be recall earlier, should the short circuit be delay slightly, and that means the recall of the wire will be delay. That is the reason why the frequency of variation of the motor movement varies with time, the mean frequency is approximately 70Hz (Rutili, 2009).

The second discrepancy of CMT is that the transfer of the molten material occurs at almost no current, whilst for the conventional short arc process it occurs at the circuit phase which means at high thermal energy. For CMT process it is not high current intensity that is responsible for igniting the arc resulting to the short circuit phase, but instead the movement of the wire that is retracted. The movement of the wire assist in transfer of the metal that occurs due to surface tension created in the melting phase. Thus, during the metal transfer phase the current is kept very low, then apparently reduces the thermal input to the work piece.

3.7 Pros and Cons of CMT/Conventional Welding process

Table 4 illustrates the major advantages and disadvantages of CMT process or conventional welding process.

Table 4 pros and cons of CMT/Conventional welding process.

Welding Process	Pros	Cons
Gas Tungsten Arc Welding (GTAW)	It generally produces defect free welds.	Deposition relates lower than the rates possibly with electrode arc processes.
	Spatter free	It is expensive to weld larger substrate above 10mm.
	Heat sources and metal are controlled independently.	It is more difficult to weld manually as the operator needs to add filler metals.
Gas Metal Arc Welding (GMAW)	Highly productive when compared to shielded metal arc welding (SMAW) and GTAW	The arc must be protected against draught.
	Minimal post welding cleaning when compared with SMAW.	Equipment have higher complexity when compared to SMAW.
	Easily Automated.	Spatter formation.
Cold Metal Transfer (CMT)	Significant reduction in heat input compared to the conventional welding process.	Short circuit phenomena don't exist for greater current
	Perfect arc length management compared with traditional process which is measured by mans of weld voltage.	The upper limits of application are close to the conventional short arc process i.e. when transition zone starts.
	Spatter free	The Lower limit of application of the process is lower compared to the conventional short circuit

3.7.1 The Limitation of CMT process

The CMT welding process has it own application limitation as with any other welding process. Figure 20 shows its area of use in a current-voltage diagram. The upper limit of application of CMT are close to the short arc process which implies that the start of arc transition zone (globular zone). Thus, the short arc process no longer exists for higher currents meaning the CMT can't be used. The lower limit of application of the process is lower than the short arc process, this gives the GMWA a wider window of application. Figure 20 represent the chart of different welding arc process, with respect to voltage and current and shows their area of application.

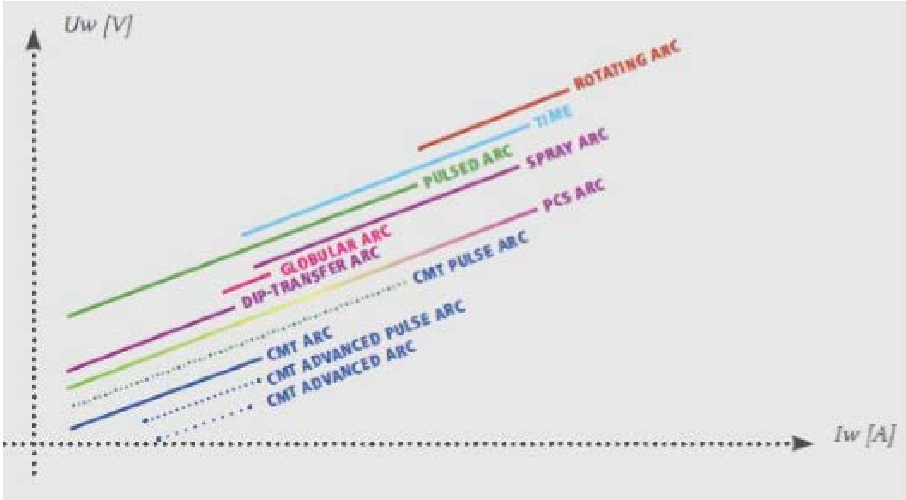


Figure 20 – Voltage -current diagram with CMT process area of application, adapted from Fronius (2017a).

3.8 Weld Bead Geometries

Weld bead geometry which comprise of bead height and width are important physical properties of a weldment. However, Dickens (1992) highlighted the important role played by welding parameter and the weld bead dimensions in determining the weld wall thickness and its influence on the effective wall width (EWW) (this implies the material that will be left over after machining) during machining. They also check the effect of surface quality on the part manufactured and check with variation of parameter one at a time. Moreover, the main aim of the research was to create an experimental and efficient knowledge, looking at the connection in between bead geometry and the key welding parameters. The parameters selected for this study were travel speed (TS), Wire diameter (WD), contact tip to work distance (CTWD), wire feed speed (WFS) and voltage, and the output parameters measured were height and width of bead geometry.

However, the result of the research showed that WD and WFS have an encouraging outcome on this study but a high TS has a negative impact. Dickens (1992) suggested that more research is needed to be carried out to evaluate the relationship between geometry and process variables in multi layered part. The basic feature of a weld is influence by the welding parameters throughout the process, consequently welding can be well spell out as multi input and multi output process. however, the major setback for manufacturer is to get the accurate control of the process inputs so as to get good welding deposition with encouraging bead geometries and weld perfection with little residual stress and distortion (Kolahan and Heidari, 2010). Moreover, bead geometries are important characteristic of a metal cladding parts. Cooling rate of weld can be estimated from the weld cross section area and the arc travel rate (BJ, 1968). The bead cross sectional area with its height and width affect the shrinkage which control residual stress and shrinkage (Adebayo, 2013). Though, the weld bead characteristics from the solidification of the liquid metal, surface tension plays an important role in defining the ultimate bead geometry. However, Apps et al. (1963) concluded from their research on submerged arc welding that several welding parameters such as travel speed and current influence the welding bead geometry. Additionally, Gurev and Stout (1963) stated that with metal inert gas welding that the bead width increases with increase in heat input into the system i.e. with either increasing the arc travel rate or decreasing the current input. He also looks onto the effects metal characteristics on bead geometry. Thus, with spray condition mode, an increase in voltage produces an increase in the width of bead with decrease in bead height, penetration and reinforcement area.

Yamane et al. (2013) stated that the bead quality is dependent on the arc process and parameters. These parameters have a greater consequence on the arc welding stability and control that determines the overall product of the weld bead, showing the occurrence or non-appearance of welding imperfections and distortion. Studies have been done on the effects of travel speed, arc voltage, wire diameter and arc current on the quality and shape of bead geometries in respect to deposition rate and penetration. Kim et al. (2003) also highlighted both investigational and modelling analysis on the impact of voltage, travel speed and welding angle on the bead on plate with GMAW. In different study, Suban and Tušek (2001) also investigated the effect of combination of shielding gas on the quality and weld bead geometry. He also studies the imperfections in welding with respect to the arc instability with GMAW welding. From this research, it was concluded that it is potentially possible to identify imperfections linked to shielding gas. Productivity determines the cost and all this depend on welding current, travel speed and electrode wire diameter. However, increasing the weld travel speed exposes the weld bead geometry to be prone to defect and this could cause a distortion to the welding process (Mendez and Eagar, 2003).

3.8.1 Weld Imperfections and Defects

Welding processes are liable to defects and imperfections. Sometimes the welding bead is in contradiction with the structural integrity, it is considered as defect otherwise imperfection. Mendez and Eagar (2003) highlighted porosity, cracking, inclusions, excessive convexity, and humping, undercutting and unfitting fusion as the key imperfections in arc welding. The origin of these imperfections is related on the welding methods and parameters. It can also be related the composition of the shielding gas and the material used. The most important imperfections and defects can be discussed in below subsection.

3.8.1.1 Porosity

Porosity is generally associated with gas for the period of the solidification of a weld bead and generally recognised as cavity-type discontinuity. For instance, Cong et al. (2015) stated that porosity formation in Aluminium is due to mutation of hydrogen solubility in the process of liquid to solid state transformation. The result summarized that using combination of good quality wire and certain synergic operating mode, porosity can be eliminated.

The key sources of these defects are (Adebayo, 2013):

- Presence of oxides with or other sources of contaminant;
- Not too satisfactory parameters;
- Insufficient flow rate of shielding gas;
- Higher welding speed, can lead to weld pool freezes before gas go away;
- Some present of impurities such as sulphur and phosphorus on weld parent material.

3.8.2 Weld Bead Humping

Humping is a defect caused because of high travel speed. It can be expatiated as the developmental occurrence of hump on a bead at consistent deposition. It can also be explained as a periodic ripple of a weld bead, with a typical sequence of ripple comprising of hump and valley as shown in Figure 21. This phenomena occurs due to the momentum of the back flow of the molten pool (Soderstrom and Mendez, 2006) and high weld travel speed (Nguyen et al., 2013) that lead to uncontrollable humping effect.

Figure 21 : Bead Humping

There are several literatures regarding high speed welding defects. For instance, BJ (1968) was the first identified report on humping with tunnelling. In addition, (Nguyen et al., 2013) gave his own opinion on humping with GMAW process. Several researchers has describes humping has it happen. BJ (1968) identified humping using laser welding and (Nguyen et al., 2013) documented that it has been projecting using electron beam welding. The discovery of humping has slow down the working on welding speeds in various fusion welding processes and had stop the growth in productivity in welding operation. In general, there is a limited knowledge regarding the main cause or physical mechanism responsible for humping. Which makes it problematic understanding the best way on how to reduce humping with retaining high welding speed (Nguyen et al., 2013).

Adebayo (2013) mentioned two types of humping which are Gouging Region Morphology (GRM) and Beaded Cylinder Morphology (BCM). GRM morphology is characterised by an open and not filled dried hole in between humping bead. Moreover, gouging region is seen in front of the weld pool that exhibits a very large depression. The bulk of the molten metal, that is called trailing region resides in the back of the weld pool. For some cases two small channel appears on the wall of the gouging region. Soderstrom and Mendez (2006) points out that tunnel porosity defects share similar mechanism with humping effects, for which the gouging effect extends under the surface of the weld and split bead weld, which the gouging region split the weld bead longitudinally. For GRM, gouging is as result of the arc force drags the molten pool to the tail of the arc. Due to the high-pressure arc in GTAW, GRM is more frequent in this welding process. In order to minimise GRM Soderstrom and Mendez (2006) suggested the used of hollow weld electrode that probably can reduce the arc pressure. However, shielding gas mixture and welding position has shown their effects on hampering. Also, using a downhill welding process, it could reduce hampering since the rear flow momentum in the welding pool are reduced using gravitational force. It is seen that reactive shielding gas comes with considerably fewer humping comparing with inert gas. The basic reason is being to reduce hampering effect, creating wider weld pool with same deposition, that is obtained by reactive gases (Soderstrom and Mendez, 2006).

Furthermore, BCM is totally different from GRM not only that the characteristic of dry spot missing but the weld reveals know evidence of depression under the work piece. The weld piece for the case has an undulating aspect. The encouraging factor in this case is reducing the surface energy, producing a sphere that formed an intermitted deposit, that act as alternative to an uninterrupted cylindrical bead. For reducing humping in this case similar approach like GRM should be applied. Additionally, it is shown that increase thermal conductivity give rise travel speed that promote humping. This is as a result of preheating the process and reducing the molten metal tail that leads to reduction in deposition

(Soderstrom and Mendez, 2006). Cho and Farson (2007) shows two conditions responsible for humping. The first being the motion brought by the surface tension pitching force while the other one is the untimely solidification of the molten pool leading to the splitting of the molten pool into front and rear portions. Humping effect is as a result of high speed welding that happens as a result of back flow momentum of the molten pool. Soderstrom and Mendez (2006) proposes downhill welding, using hollow electrodes preheating, and reactive shielding gas as method to reduce humps effect.

In addition, BJ (1968) reported a dependence on travel speed, arc current, shielding gas, voltage and electrodes conditions. For various parameter study, undercut is basically associated with humping. The rate of undercut was observed to be quite stable throughout the weld length, all of a sudden change with the occurrence of humping. Savage et al. (1979) studied this parameter in details, its effect to humps with a 20mm width of hardened steel in Tungsten metal arc welding. The important characteristic is that for a fixed rate arc current, there exist an increase in travel speed that eventually leads to humping. However, this literature was unable to get report on humping with CMT welding process.

3.9 Failure Analysis

Failure is said to have occurred when a component does not function with the design intent. However, a failure mode is a description of fault, that is, how we can observe the fault. Moreover, fault mode should probably be a more appropriate term than failure mode. IEC 50(191) recommends the use of fault mode, but the failure mode term has been widely used, that may confuse readers. To identify failure mode the output of the process has to be carefully studied. With respect to qualitative survey and cladding industry professionals, water penetration water penetration remains the most frequently failure mode of cladding. Also, Blanche and Shrivastava (1994) suggested a classification scheme for failure modes which are intermittent failures and extended failures. However, extended failure can further be divided into complete and partial failures. Moreover, the complete and partial failure may be further divided into sudden and gradual failures. Lastly, the extended failure can also be split into catastrophic and degraded failures.

However, in some application failure can be classified as either primary failure, secondary failures or command faults for example see Henley and Kumamoto 1981; Villemeur 1988. A primary failure is a failure caused by natural aging of the functional block whilst a secondary failure is a failure caused by excessive stress outside the design envelop of the functional block. This can of stress can either be from shocks from thermal, mechanical, electrical, chemical, magnetic, or radioactive energy source.

The general picture of the relationship between cause and effect is that each failure mode can be cause by several different failure causes which leads to several different failure effects. However, to obtain a broader view of the relationship between these terms, the level of pact being analysed should be brought into account. Failure causes and effects industries are being analysed using failure, Modes, Effects, and Criticality analysis (FMECA), Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). Moreover, for this thesis FTA will be use in analysing any eventuality that may occur in the cladded material.

3.9.1 FTA – Fault Tree Analysis

The fault tree technique was introduced in 1962 at Bell Telephone laboratories, in connection with a safety evaluation of the launching system for intercontinental Minuteman missile. The Boeing Company improves the technique and afterwards introduced a computer programs for both qualitative and quantitative fault tree analysis. At the moment, fault tree is the most commonly used techniques for risk and reliability studies. FTA is a deductive technique in which we start with some specified system failures or accident. The system failure or accident is called the top event of the fault tree. The immediate casual event A_1, A_2, …. that, either alone or combination may lead to the top event, that are connected by means of logic gate. Next, identifying all potential casual evens $A_{i, 1}$, $A_{i,2}$…. that may lead to event A_i for i = 1,2… However, this procedure is drive deductively (i.e., backward in the casual chain) until we reach suitable level of detail. The basic event are the events on the lowest level of the fault tree.

4 Equipment and Experiment

As a part of the ongoing CMT project, we have carried two experiment - Experiment 1 and Experiment 2. For the experiment conducted we label each as Test. Experiment 1 is the cladding of mild steel with corocarb Ni-WC as the weld filler, with CMT process of different synergy line and shielding gas. Experiment 2 is the use of CMT welding process with Inconel 625 in cladding of mild steel.

4.1 CMT Welding Equipment

The experiments were conducted in the Centria University of Science, The CMT welding equipment is generally manufactured by Fronius International GmbH. The welding equipment consist of a Transplus Synergy 400 R power source (1), FK 400 R cooling unit (3), VR 7000 CMT wire feeder (5), Robacta Drive CMT welding torch (6) and wire buffer (7). The equipment is attached to an ABB IRB 4600-40/2.55 robot unit with digital controller (4). The equipment is represented in Figure 22.

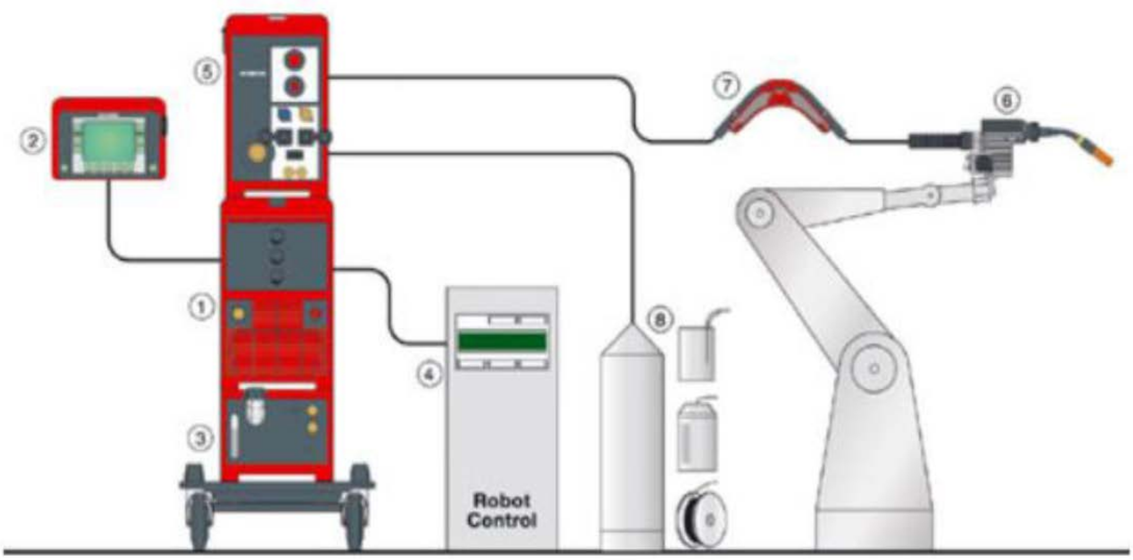


Figure 22 : CMT – Welding Equipment, adapted from (Fronius).

However, the power source is fully digitized and microprocessor-controlled MIG/MAG power source for short circuit, pulsed arc and spray. In addition, it also supports the CMT advance welding. It is designed for industrial use in automatic and robotic applications. Its welding current range from 3-400A (MIG/MAG) with a working voltage of 7-34.0V. Furthermore, synergic approach means that the welding is made easy by just selecting the material and the sheet thickness and the welding process is controlled by the machine automatically. The recommended base material for this power source are aluminium, CrNi, special metals and steels. The unit is water cooled by FK 4000 R attached at the bottom of the unit (Fronius).

VR 7000 CMT wire feeder pushes the wire from the coil into the welding torch through wire conductor with its small feeding motor. The wire buffer is an important feature of the process as the wire feeder only pushes the wire forward. The welding torch has its own motor for wire feeding and also generating the back and forth motion of the wire. The wire buffer allows the variation of the wire length, meaning that it decouples the front and rear wire drives. The wire buffer and its functionality is represented in Figure 23.

Figure 23 : Wire Buffer, adapted (Fronius).

The equipment in general, is controlled by the remote control, RCU 500i. It controls the power source along with variables related to welding via digital display. This part is connected to the system with a localNet connector. However, with this controller almost every aspect can be controlled during welding. The data bases with a preset welding programs for different welding fillers can be uploaded into it and these jobs can be altered to fit different purposes. Moreover, Jobs have certain synergy lines for materials depending on the composition and other properties of the fillers. The controller as well, store data for each welding with timestamps and welding values, which are minimum and maximum currents, voltages, job number and the number of the synergic curve used.

This welding system is connected and controlled by ABB IRB 4600-40/2.55 robot – unit. This robot - unit also includes a co-ordination (turn table, rotating table) table for the work piece. It can be move in anywhere to create welds wherever they need to be done, including cylindrical shaped rod cladding etc. Additionally, rotating table also provides good possibilities for additive manufacturing with CMT.

4.2 Experiment 1

This test was performed with corocarb Ni-WC filler wire used as the filler material on mild steel. However, the aim of the experiment is to analysed the used of CMT process in cladding, varying the welding parameters for weaving and stringer motion, selecting different synergic line and the effect of shielding gas application. In addition, the composition of the wire in the brochure is Ni-B-Si-Matrix + 62% WSC (2400 $HV_{0.2}$). Corocarb Nickel is a filler wire based on Ni-B-Si with embedded highly resistant Carbides. In addition to its excellent heat and corrosion properties, it also has excellent abrasion resistance. It consists of 62% of tungsten melted Carbide and approximately 30-40% Ni -B-Si Matrix. The alloy has a low melting interval of approximately 900-1050 ºC and it tends to form smooth and clean surface due to its excellent flow properties (Designation). Table 5 shows the shielding gas recommended by various manufacturer for different weld fillers. From Table 5, it can be inferred that Corocarb has no recommended shielding gas.

Table 5 – Shielding gas recommended

Weld Filler	***Shielding Gas***
Corocarb	*Nil*
Stoody	*Ar 75-90%, bal.* CO_2
Welding alloys	*Ar + 5-25% CO2*
Wokadur	*Ar + 2.5%* CO_2

4.2.1 Test 1: Weaving on top of mild steel, Synergy line 1357

The test was performed with a weaving width 12mm, a frequency of 2HZ, travel speed 6mm/s, ALC -30%, DC 0.0. Table 6 depicted the parameter of test 1 and the bead appearance (Figure 24). The wire burned quite well compared to previous research that generated smoke with EG 8336. The test was made with machine number 2 on Y- direction.

Table 6 – Parameter of test 1

1357	I	U	WFS	TS	f	A	advance	Arc Power	Arc Power/ WFS	Arc Power/TS	Description
Time at	*A*	*V*	*m/min*	*mm/s*	*Hz*	*mm*	*mm*			*J/mm*	
10.37	150	15.3	5	6	2	12	-	2295	459	383	Single bead
10.41	169	17.1	6	6	2	12		2890	482	482	Single bead
10.46	159	16.2	5.5	6	2	12		2576	468	429	Single Bead
10.56 - 10.56	162	16.8	5.5	6	2	12	10	2722	495	454	2 adjacent beads
	161	16.6						2673	486	445	

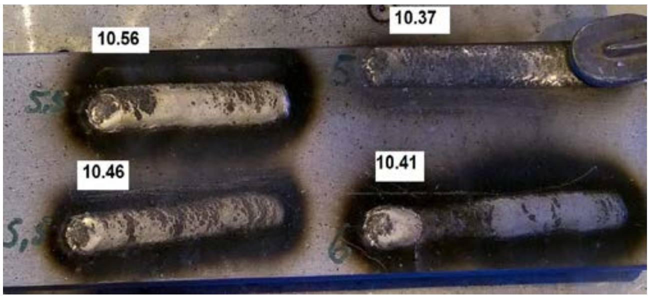


Figure 24: Test 1 bead appearance

The cross section view of experiment 10.37 was highlighted in Figure 25, it shows that there was significant penetration. However, experiment 10.37 from Table 6 with arc power 2295W, Hardness measurement with weight of 0.3kg, was 625, 600, 552, and the average is 592 HV0.3 and with one measurement of 588HV1.

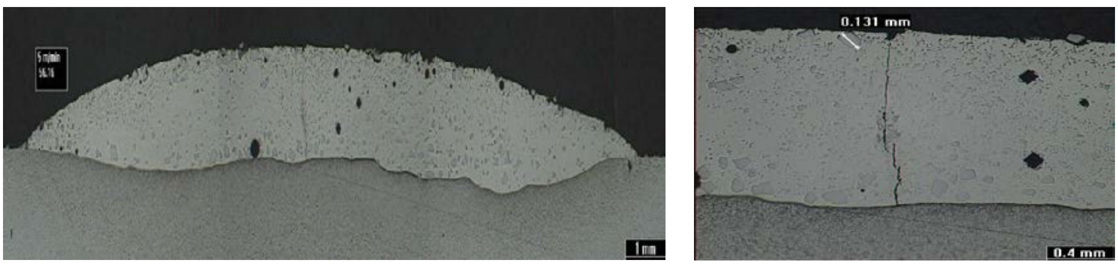


Figure 25: Test 1 at 10.37 weaving single bead wire feed 5m/min.

Also, Figure 26 is the cross section of the bead shape of single bead and adjacent overlapping bead at wire feed speed of 5.5m/min. It was seen from Figure 26b cross section view, which reveals a significant penetration and cracks.

a. b.

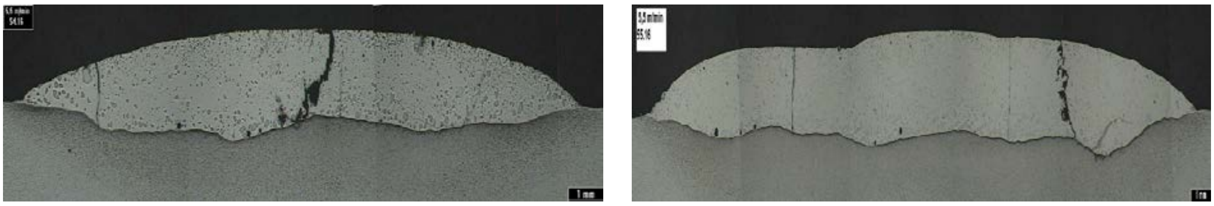


Figure 26: Test 1, a) at 10.46 weaving motion single bead and b) at 10.56 weaving motion two adjacent overlapping beads.

4.2.2 Test 2: Stringer motion, Single and Adjacent beads, Synergy line 1357

The intention of this test was to test the stringer motion, singles and adjacent test with machine 2 on Y-direction. The ALC value is 30% and DC value of -5, for some reason, though with a value +5 the spattering would be lower and power lower observed as at a later test. Table 6 depict the parameters from test 2. From Table 7, the Arc length correction and dynamic correction value is included, the travel speed is increased to 20mm/s comparing to test 1, the synergic line remain the same but the movement is changed to stringer motion.

Table 7 : Test 2 data stringer movement.

1357	I	U	WFS	TS	ALC	DC	rise	Arc Power	Arc Power/ WFS	Arc Power/TS	Description
at	*A*	*V*	*m/min*	*mm/s*	*%*		*mm*	*W*		*J/mm*	
10.05	128	10.9	3.6 (set 4)	20	-60	-5.0		1395	388	70	
10.09	148	12.1	4	20	-30	-5.0		1791	448	90	
10.19	171	16.7	5	20	-30	-5.0		2856	571	143	
10.21	187	18.2	6	20	-30	-5.0		3403	567	170	
10.29 - 10.30	171	16.2	5	20	-30	-5.0	5	2770	554	139	6adjacent beads
	166	16.6						2756	551	138	
10.39 - 10.40	181	18.3	6	20	-30	-5.0	5	3312	552	166	5 adjacent the bead
	180	18.8						3384	564	169	

The bead shape from test 2 is highlighted as Figure 27 A& B. Figure 27A shows the bead shape of test 2 for single bead and from Figure 27B, dilution changes from too small to large when WFS was increased from 4 to 5. However, the initial carbides were dissolved off from the middle of the bead and been replaced by a smaller in-situ carbide. The hardness of the matrix is 572 HV1.

A B

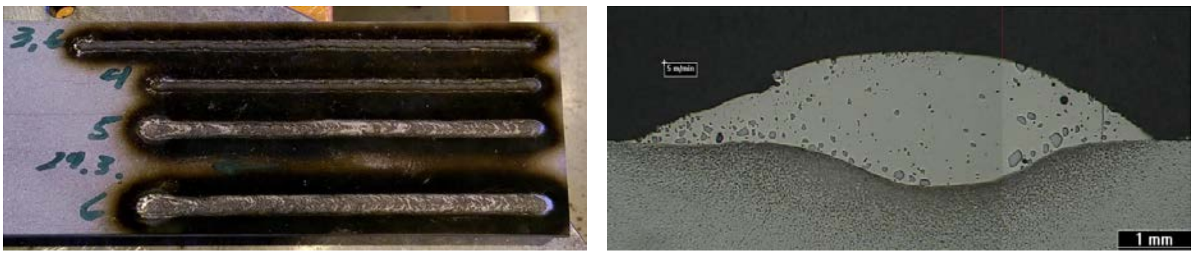


Figure 27 : Single bead test at 10.05 – 10.21 at a travelling speed of 20m/s.

Additionally, from Figure 28 cross section view, the wire feed speed was increased to 6m/min, the carbides dissolved from the middle of the bead.

Figure 28 : Wire feed speed of 6m/min. Carbides are dissolved off from the middle of the bead.

Figure 29a is the adjacent bead for wire feed speed of 5m/min, the surface did not become filled, and the cross-section figure was not made whilst Figure 29b is the wire feed speed of 6m/min, the surface became more filled up than with 5m/min wire feed and figure 30c is for the MAG process.

Figure 29 : Figure (a & b) test with adjacent bead CMT process and c) MAG process

Furthermore, Figure 29b shows that significant penetration was made through the base material. Lastly, Figure 30 represent the cross-section diagram of test with adjacent beads at 10.39 – 10.41 for a wire feed speed 6 m/min. However, significant penetration and cracking was experienced for this test.

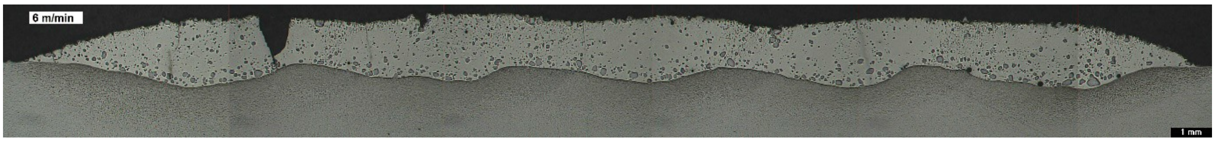


Figure 30 : Test with adjacent beads at 10.39 - 10.41 wire feed speed 6 m/min. Too large penetration, cracking.

4.2.3 Test 3: Stringer Motion, adjacent beads on top of Mild Steel, 1357

This test is performed with stringer motion on top of mild steel, the wire feed speed was reduced and a smaller rise than in test 2. The Shielding gas Mison 18, 20l/min was used with a correction factor of 1.6. The base material of 20mm mild steel was sandblasted. Lastly, the final test was held from 16.14 to 16.18 between the beads 30sec waiting to cool the fire. However, the 30sec wait between the beads has an effect on the Arc power was reduced to 2906W. The Temperature was measured for experiment 16.14-16.18 and after the last bead at 16.14 -16.18 by an infrared thermometer. Measured temperature immediately after the test was of 200 - 210°C. At the beginning of the last bead 150°C. Figure 31 depicted the bead from test at 15.55-15.56, 15.58-15.58 and the wire feed was too small and the surface did not become filled.

Table 8 : Test 3 parameter of adjacent bead on top of mild steel, 1357

1357	**I**	**U**	**WFS**	**TS**	**ALC**	**DC**	**Advance**	**Arc power**	**Arc Power/ WFS**	**Welding Energy**	Description
at	*A*	*V*	*m/min*	*mm/s*			*mm*	*W*		*J/mm*	
15.55 - 15.56	150	13.1	4	20	-30 %	-5.0	3	1965	491	98	
	150	13.2						1980	495	99	
15.58 - 15.59	170	14.1	4.5	20	-30 %	-5.0	3	2397	533	120	
	164	14.8						2427	539	121	
16.01 - 16.02	165	17.1	5	20	-30 %	-5.0	3	2822	564	141	
	169	17.9						3025	605	151	
16.14 - 16.18	175	18.6	5	20	-30 %	-5.0	3	3255	651	163	30 sec wait between the beads
	167	17.4						2906	581	145	

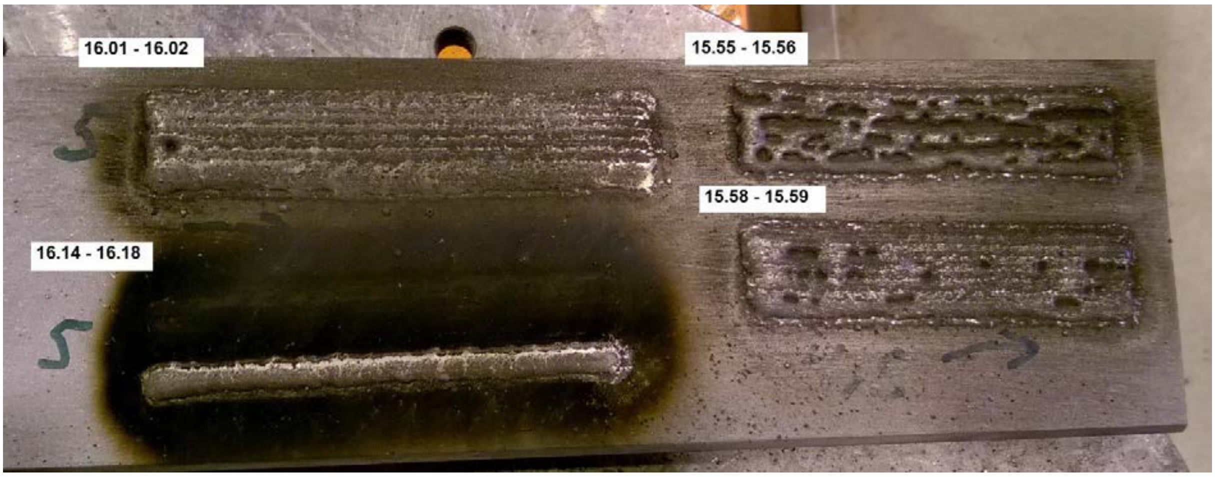


Figure 31 : Test at 15.55 - 15.56 15.58 to 15.59 and the wire feed was too small and the surface did not become filled.

For Figure 32 a (not cooled), there was significant dilution which demonstrated high temperature, penetration on the first bead is 0.7mm and the final 0.6mm. Also for figure 32b the intercooled test at 16.14-16.18 from Table 8, it can be deduced that there is significant penetration and cracks. The penetration in the last bead is about 0.5mm.

a. b.

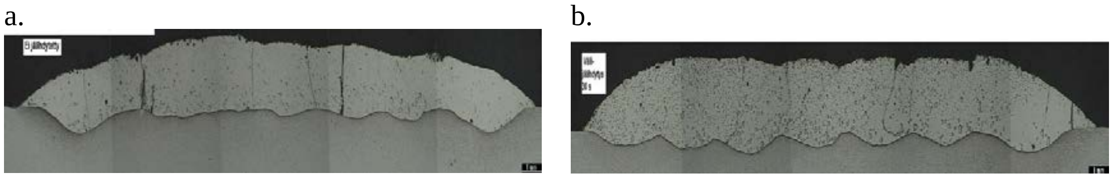


Figure 32 : a) Not cooled and b) intercooled

4.2.4 Test 4 Single Bead, line 1657

Test 4 was performed with the intention of observing the effect of Arc length correction and Dynamic correction regulation to low penetration and carbides that remain undissolved. However, the experiment of single bead test was continued. Moreover, the synergy line was change to 1657, stellite 21 on the line.

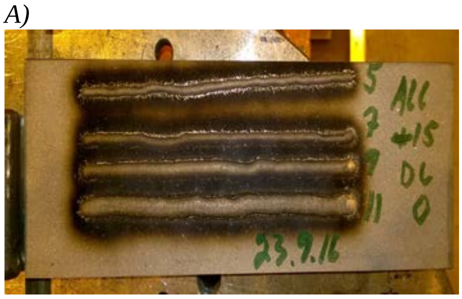
The gas nozzle distance is 12-13mm, whilst shielding gas mison 2 (Argon; 2% CO_2) is used. Finally, the major observation in this experiment is that the wire angle turned in such a way that the travel angle was a little pushing and the thread did not create straight bead. The parameters for this test is depicted in Table 9. The test result shows that the bead does not go straight which is represented in Figure 33. Table 9 shows the result for the test. Initially the ALC was set as -15 and the DC was set as Zero and the Wire feed speed was varied as (5, 7, 9 and 11m/min). This test is repeated accordingly, that is depicted in Table 8.

Table 9 : Parameter test of single bead on top of mild steel of 20mm (80mm).

1657	I	U	WFS set	WFS Hold	ALC	DC	Arc Power	Arc Power/W FS	Weld Energy.	Hardness
at	A	V	m/min	m/min	%		W	Doc	J/mm	HV1
13.20.13	143	11.4	5	5.1	**-15**	0	1630	326	98	
13.21.26	171	12.3	7	6.9	**-15**	0	2103	300	126	
13.24.22	213	14.1	9	8.7	**-15**	0	3003	334	180	393
13.25.20	248	15.0	11	10.9	**-15**	0	3720	338	223	
14.15.09	137	11.3	5	5.1	-15	**+2.5**	1548	310	93	
14.17.01	163	12.2	7	6.5	-15	**+2.5**	1989	284	119	
14.17.59	203	14.0	9	9.4	-15	**+2.5**	2842	316	170	382
14.19.43	232	14.3	11	10.3	-15	**+2.5**	3318	302	199	
14.26.18	134	10.6	5	5.2	**-30**	+2.5	1420	284	85	
14.27.24	157	11.1	7	6.0	**-30**	+2.5	1743	249	104	
14.28.22	189	12.4	9	8.0	**-30**	+2.5	2344	260	140	356
14.29.38	223	13.1	11	10.6	**-30**	+2.5	2921	266	175	
14.34.50	131	10.7	5	4.9	-30	**+5**	1402	280	84	
14.36.03	147	10.7	7	5.2	-30	**+5**	1573	225	94	
14.37.31	179	11.7	9	6.2	-30	**+5**	2094	233	125	364
14.38.26	207	12.8	11	9.0	-30	**+5**	2650	241	159	

Figure 33 is depicted figures of test 4, Showing that straight beads was not achieved for this experiment.

A)



B)

C)

D)

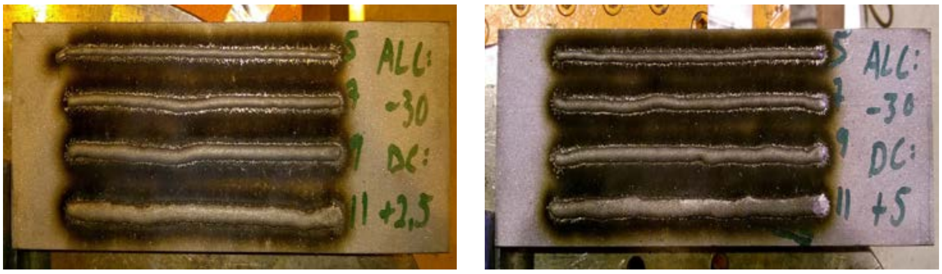


Figure 33 : Test Parameters. A) DC 0 ALC -15% B) DC 2.5 ALC -15% C) DC 2.5 ALC -30% D) DC 5.0 ALC -30%

4.2.5 Test 5 Line 1657, MAG, MAG-Pulse, Mison 18

This test is a follow up of test 4. However, the shielding gas was changed to mison 18 (Argon, 18% CO_2). Notwithstanding, Ni-WC wire manufacturer recommended gas containing more carbon dioxide. CMT (1657), a standard MAG and the MAG pulse welding process was used respectively. The parameters from this test is depicted in Table 10. For instance, CMT 1657, weave, single bead from Table 10, the wire feed speed set was varied (5, 6, 7,8m/min), ALC (-15%) and DC (+2.5) and the readings of the arc power is taken as shown in the Table 10.

Table 10 : Parameters of test 5. Atal shield gas (Mison 18) and stringer and weaving motion of single and adjacent beads black staff reading of 20 mm (80 mm) on top.

	I	U	WFS set	WFS Hold	ALC	DC	angle	A	WL	TS	Height	Arc power	Arc Power / WFS	Weld Energy
at	*A*	*V*	*m/min*	*m/min*	*%*		°	*mm*	*mm*	*mm/s*	*mm*	*W*	WFS	*J/mm*
CMT 1657, weave, single														
13.52.26	183	14.0	8	6.7	-15	+2.5	10	3	5	9	-	2562	320	285
14.01.58	171	14	7	6.4	-15	+2.5	10	3	5	9	-	2394	342	266
14.04.05	158	13.4	6	5.5	-15	+2.5	10	3	5	9	-	2117	353	235
14.05.37	140	12.8	5	5.1	-15	+2.5	10	3	5	9	-	1792	358	199
CMT 1657, Stringer, single														
14.11.08	143	12.7	5	4.6	-15	+2.5	10	-	-	16.7	-	1816	363	109
14.14.02	162	13.3	6	6.4	-15	+2.5	10	-	-	16.7	-	2155	359	129
14.16.27	184	13.7	8	7.4	-15	+2.5	10	-	-	16.7	-	2521	315	151
14.19.11	173	13.3	7	7.4	-15	+2.5	10	-	-	16.7	-	2301	329	138
CMT, 1657, Stringer, adjacent bead														
14.26.01 -	161	13.3	6		-15	+2.5	10	-	-	16,7	2.5	2141	357	128
14.27.53	160	13.5		6.1								2160	360	129
14.40.01 -	173	13.5	7		-15	+2.5	10	-	-	20	2.5	2336	334	117
14.41.40	172	13.8		6.1								2374	339	119
S 31, single														
15.37.12	194	23.3	5-8.6	-	-15	+2.5	10	-	-	16.7	-	4520	-	271
15.38.23	214	22.6	7-9	-	-15	+2.5	10	-	-	16.7	-	4836	-	290
P 1457single			WFS set m/min	WFS Hold m/min	ALC %	Pulse corr	angle °			TS				
15.41.31	125	17.4	5		-15	+2.5				16.7		2175	435	130
15.42.38	146	17.5	6		-15	+2.5				16.7		2555	426	153
15.45.12	135	19.1	5		0	0				16.7		2579	516	154
P 1457, adjacent 10 beads														
15.49.44 -	130	19.9	5	-	0	0	10	-	-	16.7	2.5	2587	517	155
15.51.36	131	19.6										2568	514	154

However, Figure 34a represent the bead for weaving, synergy line CMT 1657, the melt spread well and the beads went straight. Also, Figure 34b represent the bead for stringer motion with synergy line CMT 1657, the melt also spread well and also went straight. Figure 34c is the adjacent bead test for stringer motion with line CMT 1657, atal protective gas. TS: 16.7mm/s, WFS: 6m/min. The last bead became curved, otherwise the beads went straight. Arc power of I and U on the basis of 2150W and weighed, cross section was made and a yield of 3.3kg/h. Figure 34d shows the distance between the adjacent bead test at 14.40-14.41. Stringer motion on with line CMT 1657, atal protective gas. TS: 20mm/sec, WFS: 7m/min. In addition, the last bead is curved otherwise the beads went straight. Figure 34e is a single test at 15.37 – 15.45 for stringer motion. The first two bead with line S31 and the last three with pulsed line 1457. Atal protective gas. TS: 16.7mm/s. For the MAG process S31, the arc started to burn when the WFS operating value was raised to about 8m/min. For the pulsed arc process 1457 arc burned with WFS value 5 and 6 m/min. Figure 34f shows stringer motion with line P1457, Atal protective gas. TS: 16.7mm/s, the WFS: 5m/min. Arc power of I and U on the basis of 2575W and a weighed deposition rate 2.9kg/h. The surface appears okay and little spatter was experience. Moreover, the surface appears to the eye far more cracks than on the surfaces with CMT process. Conclusively, the bead spread with Ar-18% CO_2 gas very different way than in previous experiments with Ar-% CO_2 gas. Beads also spread well with stringer motion and it did not make snake pattern. Singles went straight unlike the experiment in test 4, Pulse-MAG line seems to produce the least energy.

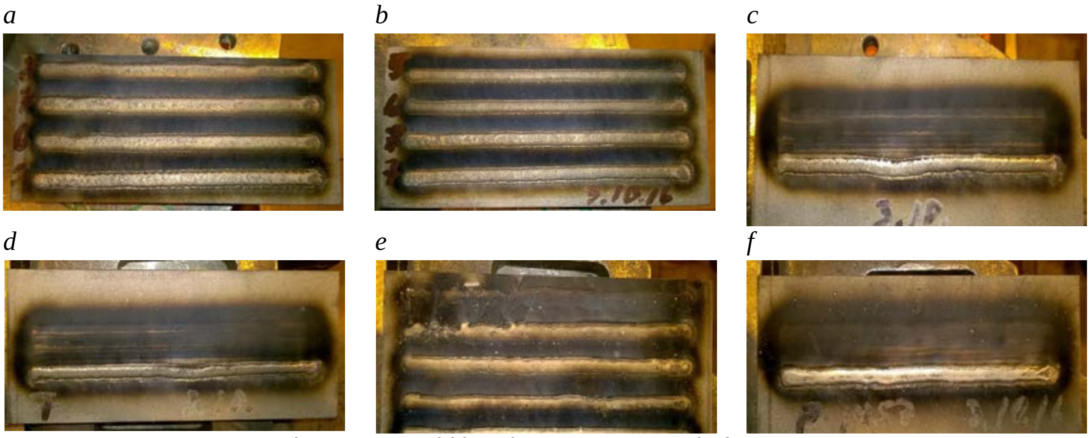


Figure 34 : Weld bead appearance made for test 5

Figure 35 shows the cross section of the bead shape for CMT 1657, marked in Table 10 current: 160A, voltage: 13.5V, arc power of 2160W, wire feed speed 6m/min. The Hardness measurement of 422 HV1 and yield of 3.3kg/hr. Pulse 1457, marked in table 10 current: 131A, Voltage: 19.6V, wire feed speed of 5m/min, arc power of 2570W. The Hardness measurement of 442 HV1 and weighed yield of 2.9kg/hr. However, CMT 1657 with a wire feed speed of 6m/min gives a lower arc power and hardness compared to pulse 1457 with wire feed of 5m/min for adjacent bead. In addition, from Table 10, CMT 1657 for stringer motion also produces lower arc power compared to pulse 1457 for wire feed speed of 6m/min as highlighted. Furthermore, from figure 35 cross section view, CMT 1657 cladding produced small dilution and no cracks while Pulsed MAG produced large dilution, cracks and carbides melted.

CMT1657 Pulse 1457

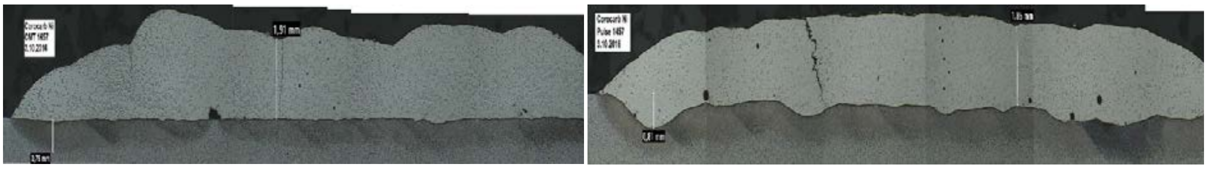


Figure 35 Cross section profile of weld produced with CMT 1657 and pulse 1457

4.3 Experiment 2

Alloy 625 of diameter 1.2mm was used in this test as the filler material, composition of this wire is presented in Table 11. The base material is mild steel with thickness of 20mm. The size of the test substrate is 100*200mm. The substrate was sandblasted and degreased prior to test.

Table 11 – Composition of the filler wire

C	***Si***	***Mn***	***P***	***S***	***Cr***	***Mo***	***Ni***	***Nb***
0,02	0,08	0,02	0,002	0,001	22,4	9,2	64,2	3,47
Cu	Ti	Al	Co	N	Fe	Pb	Ta	Mg
<0,01	0,18	0,10	0,03	NA	0,3	0,001	<0,01	0,007

Stringer single bead were made on the plate by varying parameter ALC from -30%, -15%, 0% +15% and +40%. Also, DC was varied with interval -5.0, -2.5, 0.0 and +2.5 and +5.0. The other parameters for this experiment are fixed, as depicted in Table 12.

Table 12: Parameter on Tests

Wire feed speed (Set value)	***8m/min***
Travel speed (TS)	16.7mm/s
Torch angle (work and travel angle)	Neutral, 90º
Contact tip distance	14mm
Shielding gas	Aga Mison 30He (Ar-30%He-0,03%NO)
Shielding gas flowrate	17l/min
Synergy line	1693

The parameters were choosing based on a preliminary test, which it was found that Ar-30%, He-0.03% NO shielding gas was able to produce good wetting of the bead and a relative large process parameter window. In contrast, it was found that pure Argon shielding gas was possible to weld wide and consistent stringer beads with only parameters that produce high welding power. The wire feed setting was kept at 8m/min for all test because at this value the process is spatter free and produces high deposition rate. A value of WFS higher than this could lead to spatter formation. In addition, for CMT method the wire feed speed is not constant, but the wire is reciprocating with high frequency and the mean wire feed rate is adjusted based on the feedback from the process control and actual WFS is larger than the set value.

4.3.1 Test Methods

4.3.1.1 Bead Dimension

Cross sections were prepared from each samples and bead height, penetration, dilution and contact angle were measured from the cross section. Bead width and variation were measured from low magnification microscope image of bead surface.

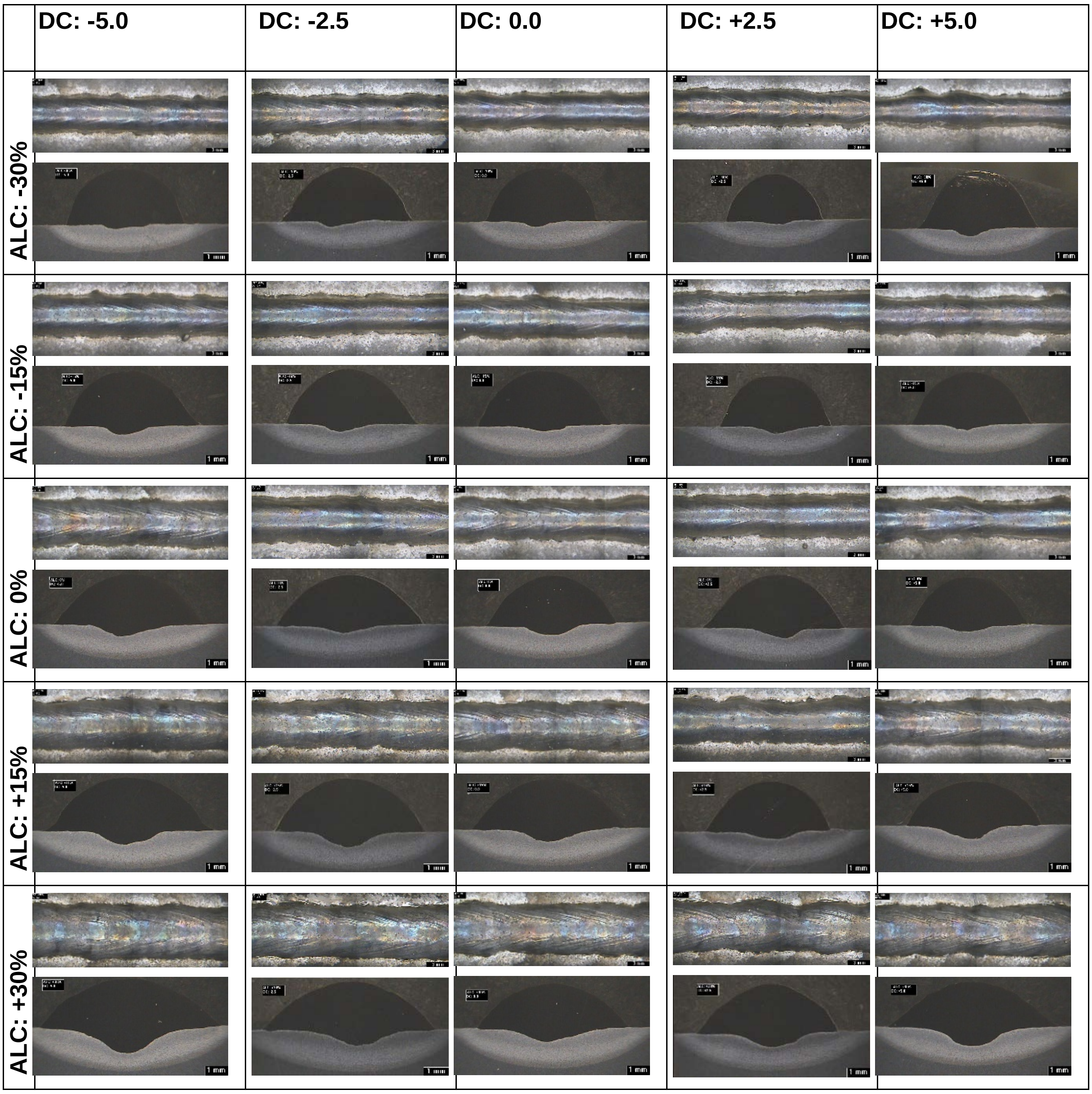


Figure 36 : Bead Surface and Cross Section image

4.3.1.2 Current and Voltage Measurements

Current and voltage during the process were monitored with picoscope 3424 oscilloscope. Current was measured with Pico TA167 current clamp that was connected close to the welding table and gave the output signal of oscilloscope. Voltage was measured between the contact tip and the cladding substrate. Sampling rate measured was 500ks/s and the period of 4s that contained total 200, 000 data samples was used on calculations. Voltage and currents values were used to determine AIP, power ratio, ratio between arcing and short circuiting, process frequency and stability of short circuiting. The effect of parameters ALC and DC on the process was examined from the shape of voltage and current graph. The average voltage, current and actual WFS value during the process were recorded from the software of the CMT power source that is able to record these values at minimum interval of 0.1s.

4.3.1.3 Bead Surface Appearance and Cross Sections

Single bead test was ranked according to bead appearance. The criteria for rejection was set as: narrow bead steep connection, poor wettability and large variation on bead width and height. Figure of bead appearance and cross section are presented on Figure 36 and the results measured on Table 12. From Figure 36, it can be deduced that has the arc length correction increases, the penetration and dilution values increases.

Table 13 represent the cross section and surface measurement results of Experiment 2. For instance, ALC -30% and DC -5; the measured parameters are penetration 0.2mm, HAZ depth 1.18, dilution 3.9%, bead height 2.15mm, Average bead width 5.1mm, contact angle 110^{o}. Comparing the result in Table 12 as highlighted moving from ALC value of 0% to 15%, it gives an increase in penetration of 0.50 to 0.61mm.

Table 13: Cross Section and Surface measurement results.

	DC	Penet-ration [mm]	HAZ depth [mm]	Dilution [%]	Bead height [mm]	Aver. bead width [mm]	Height / Width ratio	Bead width deviation	Contact angle [°]
ALC -30%	-5.0	0.20	1.18	3.9 %	2.15	5.1	0.47	0.31	110
	-2.5	0.26	1.17	3.3 %	2.37	5.2	0.46	0.29	116
	0.0	0.29	1.10	3.1 %	2.09	4.8	0.47	0.34	108
	+2.5	0.18	1.15	2.7 %	2.02	4.7	0.43	0.40	106
	+5.0	0.21	1.06	4.8 %	2.00	4.4	0.57	0.42	117
ALC -15%	-5.0	0.24	1.26	5.5 %	1.96	5.6	0.42	0.36	120
	-2.5	0.33	1.31	4.9 %	2.38	5.5	0.44	0.31	119
	0.0	0.24	1.25	5.3 %	2.11	5.3	0.45	0.42	115
	+2.5	0.33	1.29	5.8 %	2.19	5.0	0.44	0.35	113
	+5.0	0.23	1.15	3.4 %	1.96	5.1	0.44	0.50	116
ALC 0%	-5.0	0.35	1.43	9.4 %	1.98	6.3	0.35	0.38	129
	-2.5	0.34	1.42	5.2 %	2.19	6.0	0.36	0.34	128
	0.0	0.50	1.40	10.0 %	1.89	5.8	0.36	0.52	121
	+2.5	0.45	1.46	6.1 %	2.33	5.6	0.42	0.38	126
	+5.0	0.43	1.38	7.2 %	1.83	5.1	0.41	0.40	121
ALC +15%	-5.0	0.61	1.54	9.6 %	2.02	6.6	0.35	0.24	125
	-2.5	0.69	1.56	11.5 %	2.30	6.3	0.36	0.24	122
	0.0	0.75	1.54	11.3 %	1.97	6.4	0.33	0.36	126
	+2.5	0.37	1.56	8.8 %	2.16	6.1	0.36	0.33	121
	+5.0	0.63	1.44	12.8 %	1.87	6.0	0.32	0.37	119
ALC +30%	-5.0	0.67	1.69	22.8 %	2.13	7.3	0.29	0.29	134
	-2.5	0.70	1.82	14.3 %	2.12	7.2	0.30	0.26	132
	0.0	0.94	1.64	15.3 %	1.98	6.8	0.28	0.33	131
	+2.5	0.66	1.67	13.7 %	2.12	6.9	0.31	0.43	124
	+5.0	0.77	1.61	18.2 %	1.94	6.7	0.29	0.38	138

Table 14 represent the electrical result and the oscilloscope graphs are represented from figure 34 – 36. However, the average power (W) is significantly close to the AIP (W). For instance, at ALC 0% and DC value of 0.0. The Arc power is 2913W and the AIP equal to 2921W.

Table 14: Arc Characteristic value

	DC	Average			AIP [W]	Diff. I x U vs. AIP	Heat input* [J/mm]	Actual WFS m/min	Power Ratio** [W/mm^2]	Arcing ratio		Freq. [Hz]
		I [A]	U [V]	I x U [W]						Arcing %	Short IRC. %	
ALC -30%	-5.0	195	13.5	2628	2654	-1.0 %	159	8.7	270	43	57	72
	-2.5	181	12.8	2317	2569	-9.8 %	154	8.1	281	43	57	70
	0	167	12.6	2109	2354	-10.4 %	141	7.6	274	42	58	69
	+2.5	153	12.2	1867	2219	-15.9 %	133	7.1	277	41	59	68
	+5.0	139	11.9	**1661**	**2084**	-20.3 %	125	6.7	276	41	59	67
ALC -15%	-5.0	199	14.5	2893	2885	0.3 %	173	9.0	284	49	51	79
	-2.5	188	14.1	2651	2733	-2.5 %	163	8.6	280	47	53	78
	0	175	14.0	2447	2645	-7.5 %	158	8.2	286	48	52	76
	+2.5	162	13.5	2187	2436	-10.3 %	146	7.7	281	46	54	75
	+5.0	150	13.4	2013	2365	-14.9 %	142	7.5	279	47	53	74
ALC 0%	-5.0	203	15.6	3153	3095	1.9 %	185	9.3	295	54	46	85
	-2.5	194	15.5	3007	2954	0.8 %	179	9.2	287	53	47	85
	0	**186**	**15.7**	**2913**	**2921**	**-0.3 %**	**175**	**8.8**	**294**	**54**	**46**	**84**
	+2.5	172	14.8	2546	2706	-6.0 %	162	8.2	292	53	48	82
	+5.0	163	14.9	2421	2693	-10.1 %	161	8.2	291	53	47	82
ALC +15%	***-5.0***	***206***	***17.4***	***3590***	***3435***	***4.5 %***	***206***	***10.0***	***304***	***61***	***39***	***92***
	-2.5	200	17.0	3400	3243	4.8 %	194	9.6	299	61	39	92
	0	191	16.9	3219	3217	0.1 %	193	9.2	310	59	41	90
	+2.5	183	16.9	3093	3126	-1.1 %	187	9.0	308	61	39	90
	+5.0	174	16.5	2866	2970	-3.5 %	178	8.7	302	59	41	88
ALC +30%	-5.0	210	19.3	4053	3705	9.4 %	222	9.9	332	69	31	93
	-2.5	206	19.0	3914	3511	10.5 %	212	9.8	320	69	31	94
	0	196	18.7	3658	3514	4.1 %	210	9.2	338	68	32	89
	+2.5	192	18.6	3571	3347	6.2 %	201	9.2	324	68	32	90
	+5.0	183	18.4	3365	3264	3.1 %	195	8.8	329	67	33	86

*Vs. AIP, Process Efficiency factor was neglected, **Calculated from AIP power

Figure 37 – 39 represent the effect of ALC and DC on current and voltage waveform. However, studying the oscilloscope graph Figure 38 and Figure 39, and the negative effect of DC values, which is highlighted below:

- The current drops faster, however, stays on higher level during the circuit phase, which implies larger heat input during the short circuit phase.
- The frequency increases and short circuiting phase decreases as ALC increases from -30% to +30%, this can be clearly seen from Table 14. For instance, at ALC -30%, frequency equal to 72Hz and short IRC% equal to 57. Furthermore, at +30%, frequency equal to 93Hz and short IRC % equal to 31%.
- The Current and voltage phase get out of balance, voltage waveform is not regular with ALC values of 30%. This effect can be clearly seen from Figure 38 below, for which at ALC of +30% the current and voltage phase get out of order.

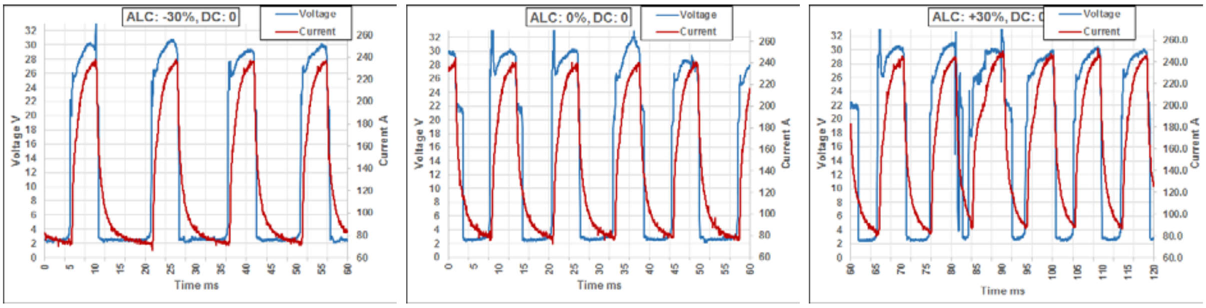


Figure 37: The effect of ALC on overall voltage and current waveform with ALC value of -30%, 0% and +30%.

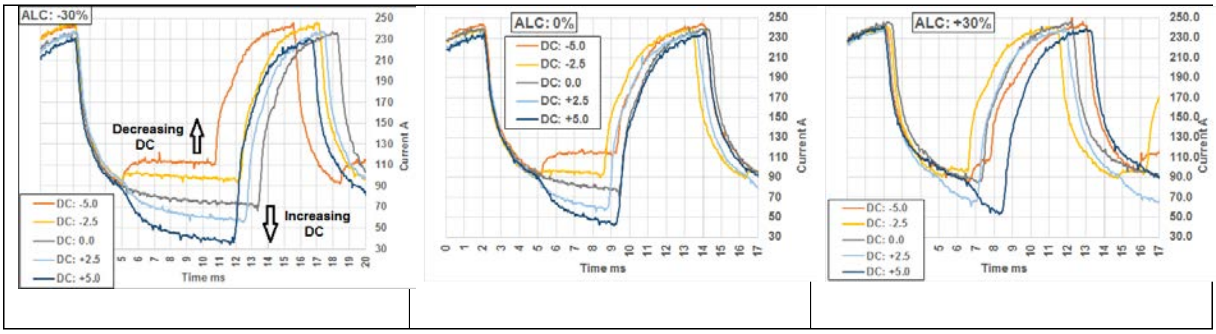


Figure 38 : The effect of Dc on current of a single phase with ALC values of –30%, 0% and +30%.

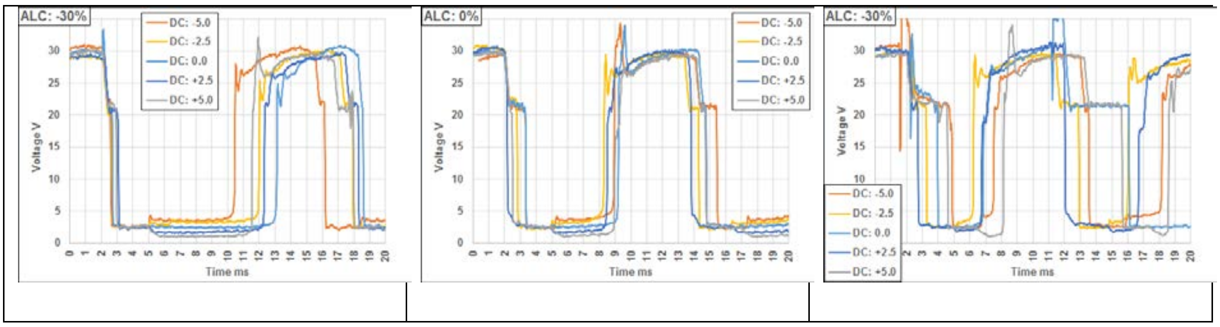


Figure 39: The effect of DC on voltage of a single phase with ALC values of -30%, 0% and +30%.

5 Results and Discussion

This chapter is discussing and summarising of the result from experiment 1 and experiment 2.

5.1 Experiment 1

For this experiment, different test was conducted with Corocarb Ni-WC has the hardfacing material. Two different synergy line for CMT process was used 1357 and 1657, with weaving, stringer motion on single and adjacent bead. Synergy line 1657 was also compared to the MAG and pulse MAG process. The shielding the gas composition was varied to see the effect on the bead. The arc length correction (ALC) and dynamic correction (DC) values was varied for this experiment. Test 4 was performed to find out the ALC and DC parameter variation effect on penetration and carbides remain undissolved in the bead. Whilst the synergy line was change to 1657 and shielding gas mison 2. It was seen from the result in Table 8 above that an increase of DC from +2.5 to +5.0 for ALC -30% result in an increase in hardness value. Figure 40 illustrates the plot of result from test 5; arc power of the process vs WFS, from the chart it is seen that DC value has effect on the arc power, the increase in DC reduces the heat input into the process. For instance, when the changes from ALC -15% and DC 0 to ALC -30% and DC +5, this process gives a decrease in the arc power for a synergy line of 1657 and corocarb Ni – WC has the hardfacing material.

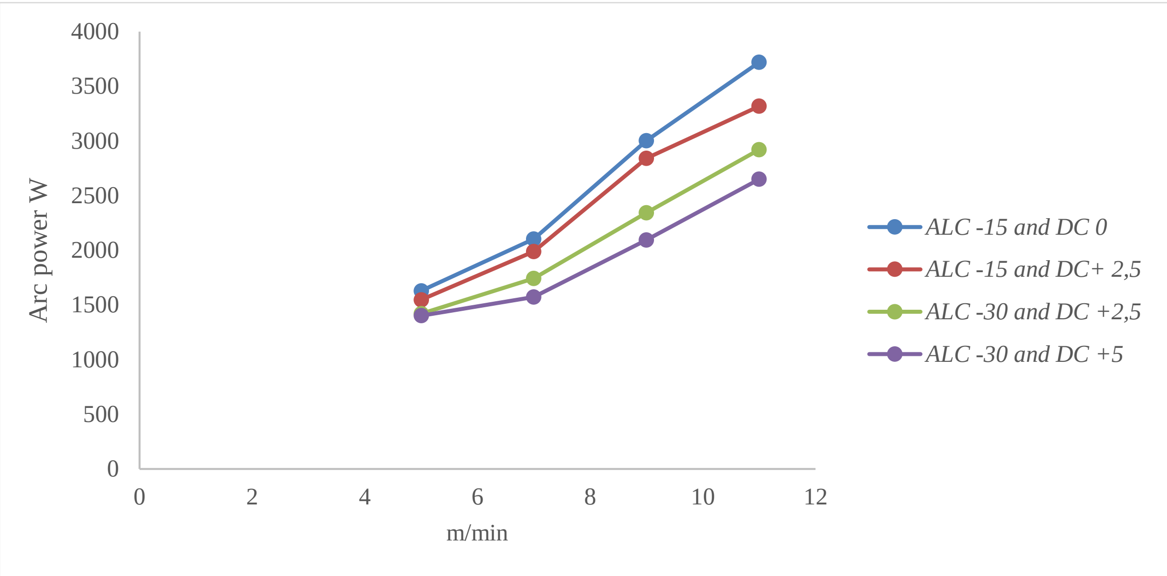


Figure 40 : Plot of Arc power vs WFS

Figure 41 is a plot of result from test 5 of weld energy versus WFS, from the chart, it is seen that CMT 1657, weave single produce the highest weld energy. CMT 1657, Stringer, Single bead produces the lowest energy because of the travel speed used 16.7mm/s comparing to CMT 1657, weave, single bead travel speed of 9mm/s. However, it is probably concluded from the chart that changing from weaving to stringer motion while cladding has no much effect in the arc power to base material.

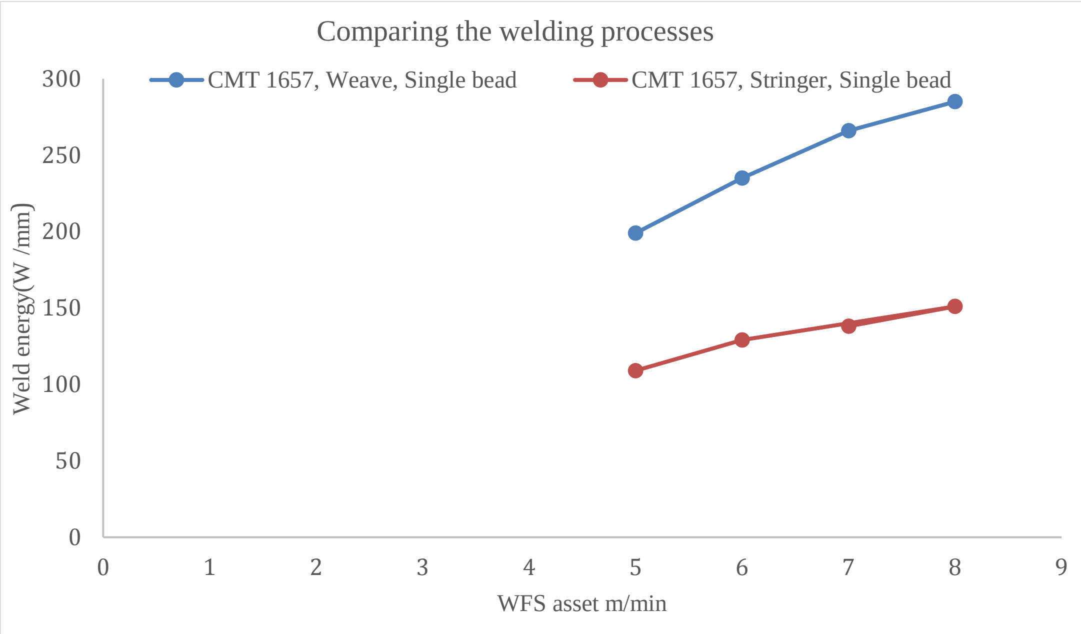


Figure 41: Plot of weld energy vs WFS

5.2 Experiment 2

The cladding of mild steel plate with alloy 625 hardfacing material was performed. However, CMT process with synergy line 1693 was used and the shielding gas is Aga mison 30 He (Ar-30%He-0.03%NO). A stringer bead was made on the plate varying the ALC and DC parameters. Moreover, the parameters used for this test is represented in table 11. Thus, the fluctuation of the set WFS value has great influence in the bead formation.

Additionally, the fluctuation of the actual wire feed speed is a characteristic feature for CMT process. Actual WFS is not stable and not the same as set value. Figure 42 represent the actual WFS values for two set values of ALC and DC recorded by fronius explorer software during the 9s welding test with a frequency of 10Hz. This values were recorded according to the rotation of the wire feed rolls. From Figure 42, it can be seen that the actual values are around 8.5 – 9.0 m/min with ALC: 0%, DC: 0.0, while 10m/min with ALC: +15%, DC: -5.0. This difference has a large effect on the actual deposition rate on resulting cladding.

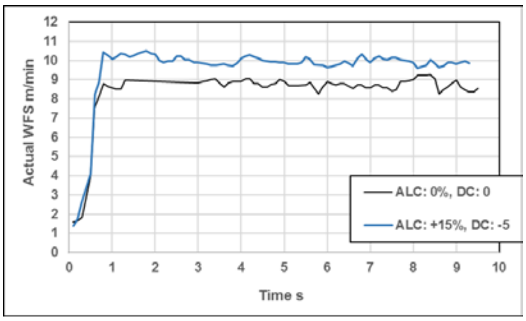


Figure 42 : Actual WFS values with ALC: 0, DC: 0.0 ALC: +15%, DC: -5.0. WFS set value 8m/min.

The results from experiment 2 was plotted to determine the influence of ALC and DC on penetration and dilution. Figure 43 represent the plot of penetration and dilution versus arc length correction (ALC).

From the chart the effect of increase in DC values on penetration and dilution of weld can be seen. However, the chat shows that for DC value of 0.0 the highest penetration is obtained and the least penetration is obtained with DC value of +2.5. Moreover, the test data shows that DC value of -5 gives a significant low penetration.

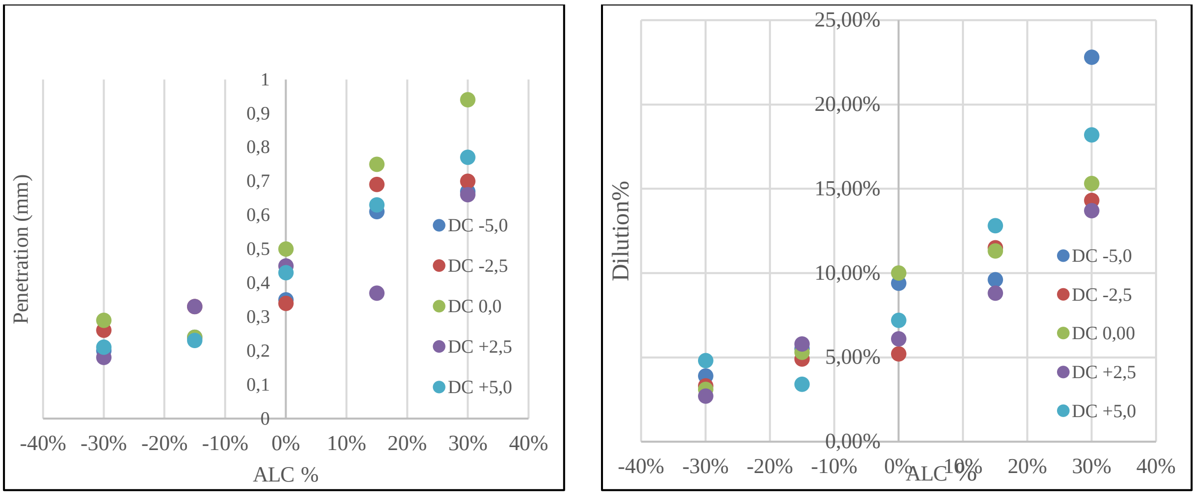


Figure 43 : Plot of penetration & Dilution vs. ALC

The Cross section and measurement result from experiment 2 is plotted to determine the effect of ALC and DC value on the bead height and contact angle. Figure 44 represent the average bead height and bead angle for different dynamic correction value. It's seen that DC value of -2.5 produces the largest bead height. Nevertheless, the DC value of -5 produces the highest bead angle can be seen in Figure 44. Pickin et al. (2011) relates the weld bead contact angle with the base material to identify the limits of cladding, stating that an angle less than 90° does not only resulted in non-uniform bead shape deposition but potential void could occur between each successive weld cladding pass. Also, DC value -5 produces the highest weld energy with no spatter during welding.

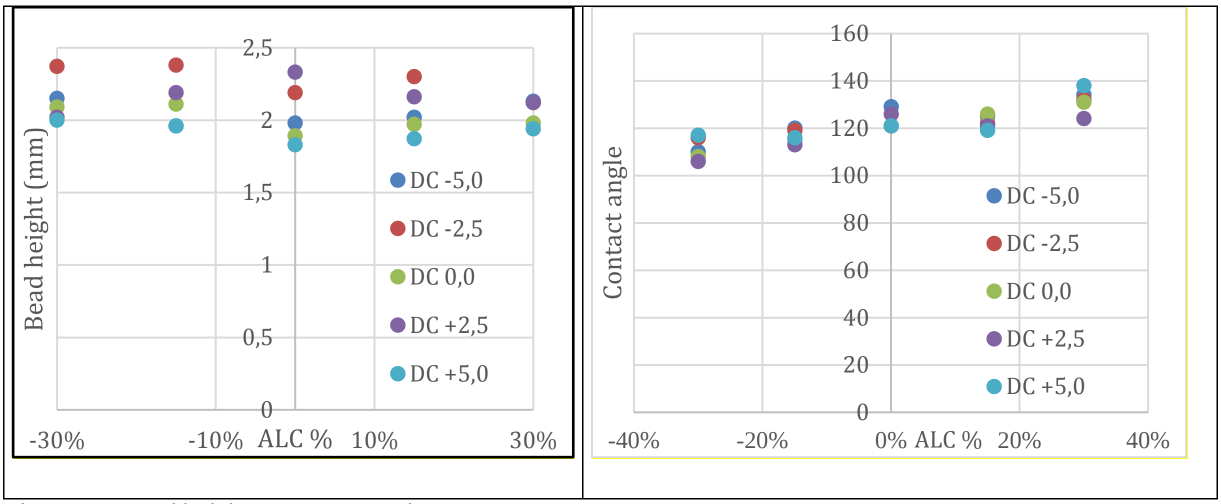


Figure 44: Bead height & Contact angle Vs ALC

- **Arc Characteristic**

The Variation of the parameter ALC and DC have great effect on the welding power under the same synergic line. Whilst the welding arc is determined by multiplying the average voltage and current, the difference between the smallest arc power of 1661 W (ALC: -30%, DC: +5.0) compared to the largest

4053 W 4053 W (ALC: +30%, DC: -5.0) is much. However, this difference is small with average instantaneous power (AIP), the smallest power was 2084 W and largest 3705 W. Moreover, if the actual WFS is taking into consideration the differences get smaller.

Furthermore, highly positive ALC value (+30%) produced some level of instability and the process is moved out of order. Current and voltage are not on the same phase anymore, but there is large deviation on the voltage phase. The cause of this can't be verified with respect to the oscilloscope graph, probably high speed camera could be needed.

Nevertheless, the changes in ALC values have only little effect on the peak voltage during arcing phase. It has effect to the average voltage by increasing the ratio of arcing versus short circuiting.

Lastly, the parameter DC affects the level or current during the short-circuiting phase and also on the total welding power. However, there wasn't any sudden change in current detected even with the smallest DC value of – 5.0 during the short circuit phase. Neither any spattering.

5.3 Case study of fault tree analysis for cladding process

Fault tree analysis was performed for hot cracking that can probably be experienced during cladding. Qualitative fault tree analysis was performed, the unavailability of failure data was one of the challenges that prevented carrying out a quantitative analysis, which is probably more precise. Figure 45 – 48 represent the qualitative fault tree analysis for hot cracking process experience while cladding.

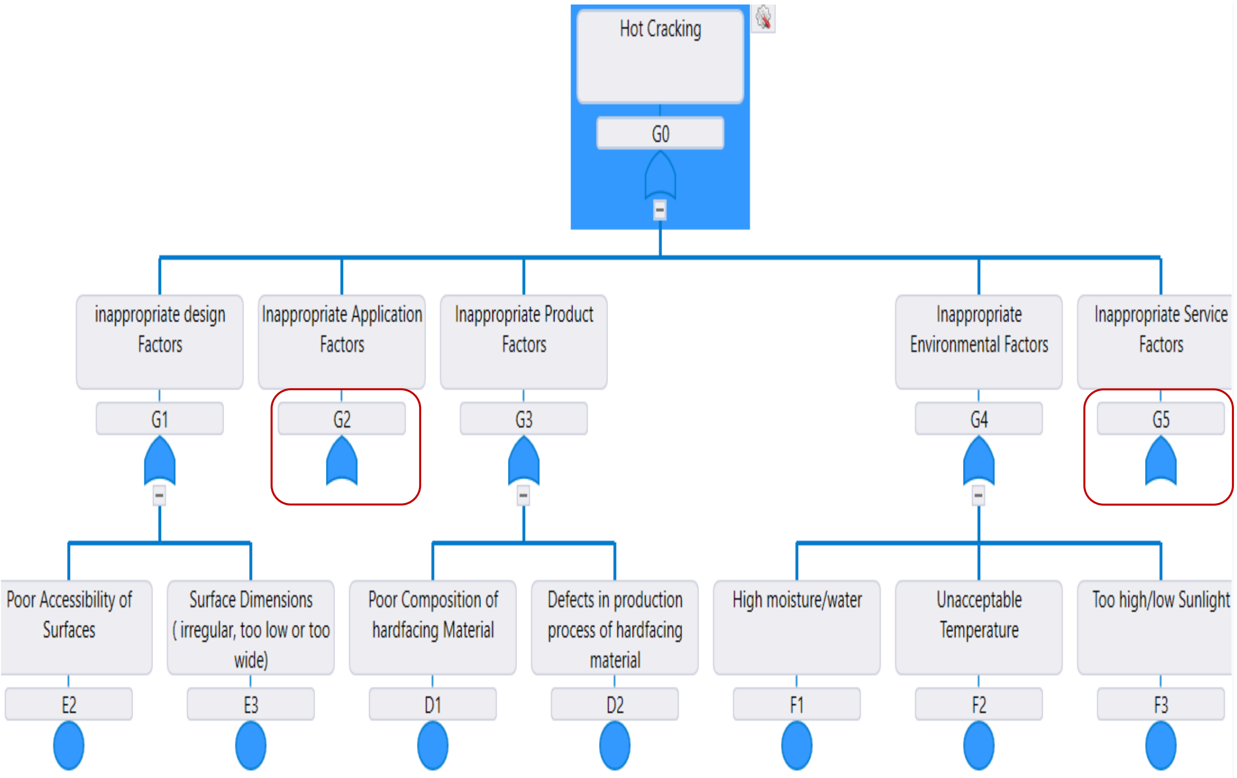


Figure 45 : Fault tree analysis for hot cracking

G5 –

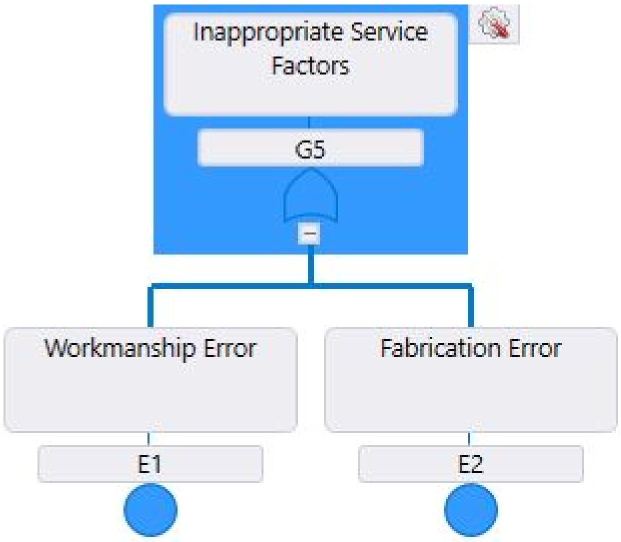


Figure 46 : Fault tree analysis for inappropriate service factors

G2 -

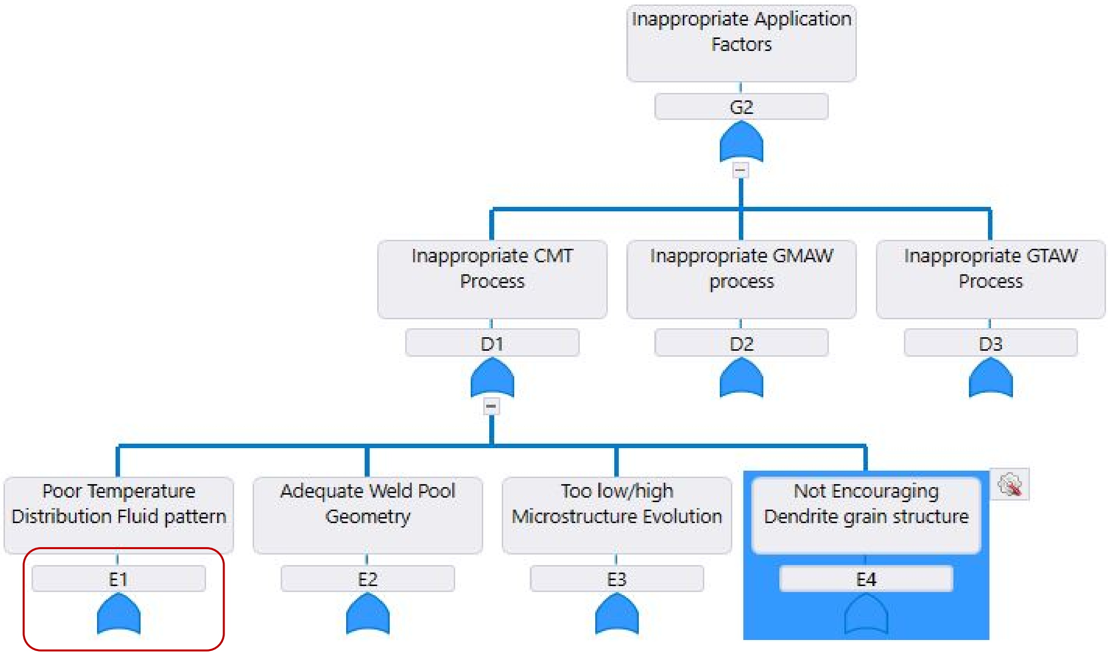


Figure 47 : Fault tree analysis for inappropriate application factors

E1 -

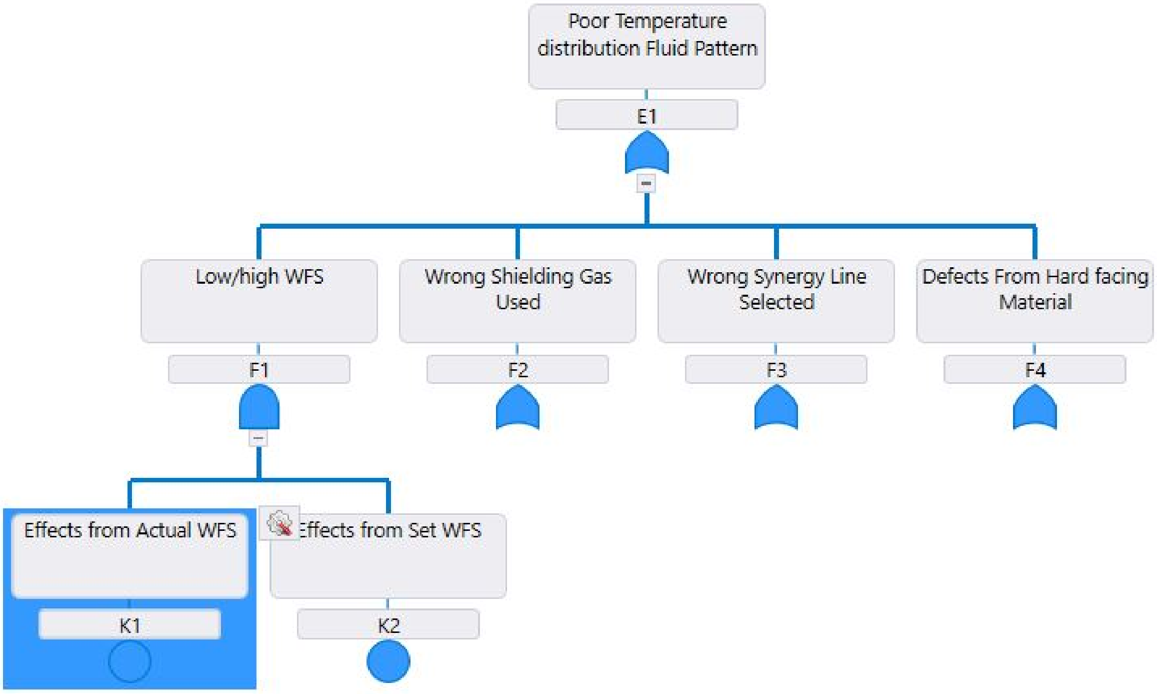


Figure 48 : Fault tree analysis for poor temperature distribution fluid pattern

6 Conclusion

The main goal of this thesis was to investigate the correctness of CMT welding process in cladding of mild steel. However, the experiment was in two part – Experiment 1 and Experiment 2.

- In *Experiment 1,* two different Synergy lines was used (Line 1357 and 1657) and the hardfacing material is corocarb Ni-WC.
- Whilst *Experiment 2* the hardfacing material was Inconel 625.

6.1 Corocarb Ni-WC facing

Certainly, among the different method tested, for an increased in wire feed speed to 6m/min in test 2 and adjusting of arc length correction (ALC) and dynamic correction (DC) parameter, there was probably dissolves in carbides present in the bead for stringer motion and single bead. Moreover, the level of hardness achieved while adjusting the ALC and DC value, for wire feed speed variation from (5-11m/min) is (HV_1 356 - 393) for test 4. In fact, for test 4 straight beads were not produced. Finally, in test 5, the shielding gas was changed, the bead went quite straight and the melt spread well. Comparing, the CMT process to Pulse MAG, CMT process produces small dilution and no crack while pulsed MAG produces significant crack. This implies that CMT seems to produce better coating with NI-WC wire compared to MAG pulsed process. Moreover, the change in synergic line for CMT process from Line 1357 to 1657 does not really affect the cladding process while cladding with corocarb Ni – WC facing. Furthermore, the results obtained from this experiment is promising, the weld energy is within the acceptable limit. Also, an increase in WFS with a value of less than or equal to 1.5 will give almost same heat input, because of the fluctuation of WFS set value.

In the method tested, the said results allow the identification of valid solution for facing in small to medium sized details, in which typical facing processes and high deposition rate can be uneconomical and disturbing, especially their high heat input.

6.2 Inconel 625

The arc power calculated from average current and voltage related well with the AIP value that were determined by oscilloscope while adjusting parameter ALC and DC are around the middle of the scale. However, with respect to the results, it is advantageous to use large negative value of DC. Value -5 did not probably produce spattering, but it increase melting range, contact angle values, without significant effect on penetration and dilution. Moreover, positive value of DC value does not show positive effect. Also, it is possible to set WFS to 10m/min, this will give the same result instead of bringing more heat to the system.

7 Research Contribution

This project contributes to a better understanding of CMT process and its application in laser cladding, additive manufacturing, etc. In the research study, the state-of-the-art of current CMT methods are mapped. Further, the study specified the critical parameters related to CMT, assessed the pros and cons of CMT process, and investigated the use of CMT process. The research contribution of this thesis can be summarized as follows:

- This research has assisted in determining welding parameters that are suitable for users applying CMT welding equipment for cladding.
- Moreover, the study gives insight that with CMT welding process a bead height of approximately 3mm can be achieved with single bead unlike the conventional welding process.
- Furthermore, the research affirms the robustness of CMT process, for instance, CMT produce bead with little dilution and no cracking with Ni-WC while comparing with pulsed MAG.
- In addition, the qualitative fault tree analysis can assist to mitigate failure occurrence while cladding.
- Further, this research has found out that, changes in ALC and DC, can lead to a decrease in the arc power for a synergy line.

8 Suggestion for further research

The base material used for this thesis is mild steel, because of some of the basic cons of mild steel compare to stainless steel. However, I suggest that further research should be carried out with a base material that have high yield strength. Furthermore, a quantitative fault tree analysis for hot cracking should be performed.

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