Andrea Gómez Fernández

AUTOMATED REMANUFACTURING AND UPGRADING OF LARGE INDUSTRIAL EQUIPMENT

Master in Materials Science

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Faculty of Engineering and Natural Sciences and
Polytechnical University of Madrid
Examiner: Senior Research Dr. Tech Jari Tuominen
Examiner: Research Manager Jorma Vihinen
Examiner: Professor Petri Vuoristo
Examiner: Professor Mihaela Iordachescu
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To my parents and my sister Micaela, for the unconditional support and help they have given to me at all times, especially when I decided to finish my studies in Tampere (Finland), where, despite the distance, your support has been especially importance.

ABSTRACT

Andrea Gómez Fernández: Automated remanufacturing and upgrading of large industrial equipment
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The objective of this master's thesis is to remanufacture and upgrade a worn area of large industrial equipment that has suffered from wear and corrosion, using an inexpensive directed energy deposition (DED) process called wire + arc additive manufacturing (WAAM).

Cold Metal Transfer (CMT) WAAM technique is used to build-up the component back to the original dimensions. To evaluate the amount of wear and estimate the magnitude of pre-machining, the worn-off area was first 3D laser scanned and compared to the original part by using a 3D CAD model. The worn area was machined and welded with filler and hard-facing alloy in order to obtain a new piece that is strong enough to perform the desired work. The filler alloy was high-strength low alloy steel (HSLA). The hard-facing alloy candidates consisted of various Fe-based and WC/W_2C-reinforced Ni-based alloys.

Tensile tests were carried out to validate the adhesion between the base material made of case hardening steel and filler metal. High-stress dry-pot impact-erosion wear tests using coarse granite abrasives were made to prove and validate the hard-facing alloys' wear resistance with respect to case-hardened steel.

According to the mechanical tests, heat-affected zone (HAZ) and fusion line between the base material and filler alloy survived the tensile tests without fracture. The fracture took place in the welded filler alloy indicating the weakest zone in the remanufactured component. The best hard-facing alloys outperformed the case-hardened steel in wear tests.

Once the best hard-facing alloy was selected, a replica was welded and finally inspected with the 3D laser scanner to guarantee the desired dimensions.

Key words: remanufacturing, WAAM, CMT, 3D laser scanning, tensile testing, wear

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RESUMEN

Andrea Gómez Fernández: Reconstrucción y mejora automatizada de grandes equipos industriales
Trabajo Fin de Máster
Universidad de Tampere, Universidad Politécnica de Madrid
Máster en Ciencia de Materiales
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El objetivo de esta tesis es reconstruir y mejorar el área dañada presentes en grandes equipos industriales que han sufrido desgaste y corrosión, utilizando un proceso económico de deposición directa de energía (DED) denominada fabricación aditiva de alambre + arco (WAAM).

La técnica WAAM de transferencia de metal en frío (CMT) se utiliza para reconstruir el componente dañado para que vuelva a las dimensiones originales. Para evaluar la cantidad de desgaste y estimar la magnitud del premecanizado, el área desgastada se sometió a un escáner láser 3D y se comparó con la pieza original utilizando un modelo CAD 3D. El área desgastada fue mecanizada y soldada con material de aporte y una aleación de revestimiento para obtener una nueva pieza lo suficientemente resistente para realizar el trabajo deseado. El material de aporte era acero de baja aleación y alta resistencia (HSLA). Las aleaciones propuestas para el revestimiento consistieron en distintas aleaciones de base-Fe y de base-Ni reforzado con WC/W_2C.

Se llevan a cabo ensayos de tracción para validar la adhesión entre el material base, de acero cementado, y el metal de aporte. Se realizaron pruebas de desgaste de erosión por impacto en recipientes en seco de alta tensión utilizando abrasivos de granito grueso para probar y validar la resistencia al desgaste de las aleaciones de revestimiento con respecto al acero cementado.

Según las pruebas mecánicas, la zona afectada térmicamente (HAZ) y la línea de fusión entre el material base y la aleación del material de aporte soportaron las pruebas de tracción sin fracturarse. La fractura tuvo lugar en la aleación del material de aporte soldada, correspondiente con la estructura más débil en el componente remanufacturado. Las mejores aleaciones de revestimiento superaron al acero cementado en las pruebas de desgaste.

Una vez seleccionada la mejor aleación de revestimiento, se suelda una réplica y, finalmente, se inspecciona de nuevo con el escáner láser 3D para garantizar las dimensiones deseadas.

Palabras clave: remanufactura, WAAM, CMT, escáner con láser 3D, pruebas de tracción, desgaste

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Preface

The work presented in this thesis was carried out within the CINEMA project, which was financed by the European Regional Development Fund under the programme Interreg North 2014-2020.

First of all, I want to thank especially my dedication and patience to my supervisor Jari Tuominen, for the time he has dedicated to me, for guiding and advising me during all these months in Tampere, as well as being always ready to answer all my questions.

To the people of the Department of Konetalo building of the Tampere University, especially to my colleagues Enni and Aki, who have so kindly helped me in the Chemistry Laboratory, teaching me to use the cutter machine, polisher, hardness machine and optical microscope; and Jorma Vihinen, my second supervisor, for helping me with the Polyworks program and the 3D laser scanning method.

To my family: my father, my mother and my sister, for always being willing to help me in anything and worrying about me at all times and for the support and affection that they always give me and they will surely continue to give me now that it begins for me a new stage in my life.

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In Tampere, Finland, on 18 September 2020

Andrea Gómez Fernández

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LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternative Current
ALC	Arc Length Correction
CMM	Coordinate Measuring Machines
CMT	Cold Metal Transfer
DC	Dynamic Correction
DED	Directed Energy Deposition
EMI	Electromagnetic Interference
EOL	End of Life
FTC	Fused Tungsten Carbide
GMAW	Gas Metal Arc Welding
HAZ	Heat Affected Zone
HSLA	High Strength Low Alloy
MIG/MAG	Metal Inert Gas/Metal Active Gas
MMC	Metal Matrix Composites
OEM	Original Equipment Manufacturer
PTA	Plasma Transferred Arc
SAW	Submerged Arc Welding
TIG	Tungsten Inert Gas
WAAM	Wire + Arc Additive Manufacturing
WFR	Wire Feed Rate

1. INTRODUCTION

Wear is a process in which material is removed from the surfaces of components or by which these surfaces are seriously disturbed. In order to reduce wear, it is important to understand the mechanism by which it occurs in each case [1]. Wear is often encountered in moving and sliding contacts or where lubrication is ineffective. Wear prevention is one of the main concerns in the industrial sector due to industrial components suffer from this problem. Damages from wear leads to substantial economic losses, so counter measures are a necessity to avoid wear losses. As wear is not a material property but rather a system property, any changes in the system can alter the wear rate. It is one of the reasons that wear characterization is complex, as wear rate varies in different environments [2] [3] [4].

Corrosion is an all-too-common result of electrochemical reactions between materials and substances in their environment [5]. Corrosion can be defined as a phenomenon which consists of the process of deterioration of metallic materials through chemical and electrochemical reactions [6]. These corrosion processes are controlled by reduction-oxidation reactions. The combined effects of wear and corrosion can result in total material losses that are much greater than the additive effects of each process taken alone, which indicates a synergism between the two processes. Corrosion accompanies the wear process to some extent in all environments, except in vacuum and inert atmospheres. Corrosion and wear often combine to cause aggressive damage in several industries, such as mining, mineral processing, chemical processing, pulp and paper production, and energy production. These two processes involve many mechanisms, the combined actions of which lead to the mutual reinforcement of their effectiveness. Application of corrosion-resistant coatings is one of the most widely used means of protecting steel trying to avoid the problem of the corrosion in the materials affected [7].

It is important to remark remanufacturing process which is gaining more and more importance in the industrial field because its positive economic and environmental impacts.

In this project, remanufacturing process will be used to achieve the objective of the thesis. To do that, the following steps will be done. First, a 3D scanning method of the worn part will be used, then said worn area will be machined to work with it, it will be welded with filler material and hard coating material, the adhesion and wear properties will be validated to ensure that the new piece is strong enough to perform the desired work and finally, a scan inspection will be performed to verify that everything is correct.

2. CIRCULAR ECONOMY

Circular economy is an economy model where products, components and materials are always aimed to be kept at their highest utility and value, and the generation of waste is minimized. Climate change and diminishing raw material resources demand transition from current linear economy model, which is based on a ‘produce-use-throw’ concept, to a circular economy model where the usage of critical raw materials and fossil fuels is minimized. This concept occurs in manufacturing industries, which consume natural resources and energy for producing new machinery, parts and products for increasing population on the globe [8]. The main objective of circular economy is to be able to reuse, recycle and utilize the waste material as a new one to minimize costs and energy in the process of manufacturing new materials. Remanufacturing and eco-design of products are focusing on this topic [8].

Eco-design and remanufacturing of components, machinery and equipment are essential concepts in circular economy, which aims to minimize waste and energy use. Reusing, recycling and utilization of waste material are the key concepts which in the circular economy, remanufacturing and eco-design of products try to focus on [8].

2.1 Remanufacturing

Remanufacturing process can be defined as an industrial process by which a previous sold or leased product or part is returned through a controlled, reproducible and sustainable process to a ‘like-new’ or ‘better-than-new’ condition in performance level and quality [9]. Economic drives for remanufacturing may include reduced costs, reduced prices to the customer, supply risk mitigation and stronger value chain relationships [10].

A few years ago, the remanufacturing engineering has become one of the most effective strategies, followed by industries, in managing of the 'end-of-life' (EOL) product and, at the same time, is an essential part of circular economy [8].

Because remanufacturing obtains much higher benefits than recycling, remanufacturing can be said to be much more profitable for original equipment manufacturers (OEMs). Regarding environmental impact, remanufacturing is characterized by protecting the environment and, for this, the remanufactured components have a much smaller carbon footprint than the equivalent originally manufactured products [8].

Generally, there have been three (EOL) strategies available for manufacturing companies:

1- *Reuse strategy*: use end-of-life product with little or no treatment before extending life usage
2- *Recycle strategy*: take end-of-life product as a supplier of the primary materials
3- *Remanufacturing strategy*: look at the used product as the 'core', in which the used parts might be reconditioned to like new ones or be restored with updated features

Remanufacturing is the best option if the product is not adequately designed for reusing and recycling processes. Remanufacturing process can be conducted by:

1- *OEM*, for instance Caterpillar Inc. remanufactures Caterpillar tractors.
2- *Owner of the product*, a specific Company, which owns the Caterpillar tractor, repairs/remanufactures it by itself.
3- *Third party remanufacturers the tractor*, that is Caterpillar Inc., or a specific Company hires some welding/cladding company to remanufacture the tractor (for example, Kokkola LCC)

Direct energy deposition (DED) techniques (laser cladding, low heat input cold-arc cladding and various thermal spraying techniques) will be relevant in the remanufacturing technologies for circular economy, since these methods use added high performance materials in powder or wire form to build up components to their original dimensions. All of them play an important role in the remanufacturing of mechanical equipment and parts with high precision, low heat effect on the base material, low distortion, excellent mechanical properties of the deposited layer, dense deposited structure and negligible dilution rate [8].

The typical workflow in remanufacturing presents different steps as shown in Figure 1. Firstly, a product is manufactured to a specific function. This product reaches its end of use cycle after which it is necessary to collect the core (worn or failed product/part) and return it to the remanufacturing process. The next step consists of inspections and evaluations of the ‘end-of-use’ to ensure the remanufacturability of this part of the product. If this part is not remanufacturable, the unusable part is recycled. In the case of this core can be remanufactured, it is necessary to make sure if the core requires disassembly process. If it requires disassembly, the core will be disassembled, cleaned and inspected/tested again. Inspection is typically conducted manually using, for instance, visual, magnetic particle, dye penetrant and X-ray techniques. Finally, the product is reassembled and finished. Before sending the remanufactured product back to the supply chain, it is inspected one again, and its performance verified. On the other hand, if the core does not require disassembly, the remanufacturing steps include inspection, part replacements or restoring, finishing and performance verification before sending it back to the supply chain [9]. In the scheme below, it is possible to observe the process of remanufacturing explained above.

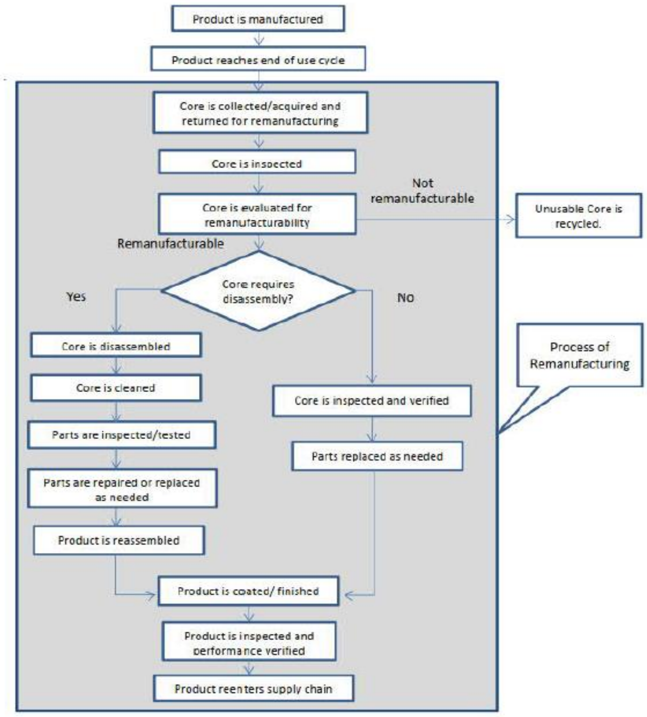


Figure 1. Scheme of process of remanufacturing [9]

The additive manufacturing or direct deposition of metal consists of processing the 3D part model, machine path programming as well as the substrate and fixture preparation to be able to retain the work piece during the deposition process as illustrated in Figure 2. Following this process, the work piece is subjected to a post deposition processing to obtain the desired dimensional requirements [11].

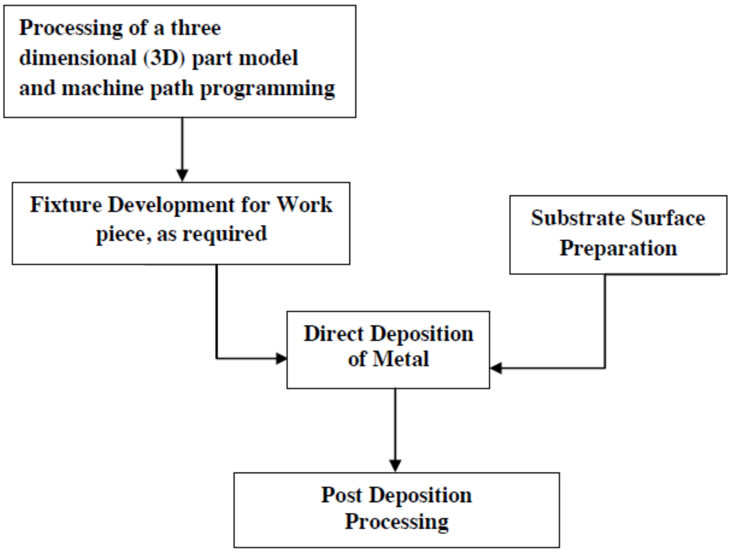


Figure 2. Direct Deposition of Metal Process [11]

The metal deposition process is conducted under an inert atmosphere or under vacuum. The surface of a substrate is prepared and then heated using a heat input such as laser or electron beam to form a melt pool. A feed material is directed onto the substrate melt pool. The deposition thickness and width can vary, and multiple layers can be applied to increase the deposition thickness [11].

2.2 Eco-design

The possibility to repair, remanufacture or recycle a product, including its components and materials, depends on the initial design of this specific product. The smart product design, which takes these issues into consideration is called *eco-design*. In more general terms, eco-design is a type of design that takes the environment into account, minimizing the consumption of energy and natural resource as well as the production of waste and emissions. Therefore, a design process is in key position to influence the operating methods and materials used in the production of products. In manufacturing industries and engineering where the mechanical components are made from metals, eco-design considers selection of materials, production process, use, energy consumption in use, durability, recyclability, modularity, upgradeability, design for disassembly, reparability and maintainability of products. These factors are not yet largely considered in heavy engineering and manufacturing, hence eco-design in these sectors would give a large contribution to transition from linear to circular economy model [8].

3. ADDITIVE TECHNOLOGIES IN REMANUFACTURING

Directed energy deposition (DED) technologies refer to a category of additive manufacturing or fabricating of 3D object by utilizing focused energy source, such as plasma arc, laser beam or electron beam, to melt the material deposited by a nozzle in the form of wire or powder. In many cases, the use of DED as a coating process is synonymous with laser cladding, although enhanced by the ability to direct the deposition to small areas. Hence, while not usually thought of as a coating process in the additive manufacturing community, in addition to being able to create free-standing 3D structures, DED can also be used to coat existing structures [12].

The added advantage of being able to direct the deposition to small areas with a high degree or precision means that DED methods have found important applications in repair of failures or defects, in providing a wear-resistant coating to an area, or and in protecting specific areas of an object from corrosion. In our case, it will be focus on repairing failures and providing a wear resistant coating in a particular area [13].

3.1 Laser cladding

Laser cladding is a welding process which uses added material in powder or wire form to surface components, to build up and restore high value components to their original dimensions. This method uses laser technology, computer-aided design and manufacturing, robotics, sensors, control and powder metallurgy.

Laser cladding is a method of depositing material by which a powdered or wire feedstock material is melted and consolidated by use of a laser to resurface or fabricate a near-net-shape part, such as in additive manufacturing [14].

Laser cladding presents several advantages comparing with other techniques, for example [15]:

- Fusion/metallurgical bond (getting the coatings won not peel-off)
- Best technique for coating any shape to increase lifetime of wearing parts
- Well adapted for near-net-shape manufacturing
- Low deformation of the substrate and small heat affected zone (HAZ)
- Fine microstructure due to a high cooling rate (rapid solidification)
- Wide material flexibility (metals and metal matrix composites (MMC))
- Life extender of components (up to 5 times)
- Low dilution even in mono-layer coatings (chemical transformation of the base material)
- Less post-processing afterwards
- Low operation costs
- Fast, accurate and easy to automate increases productivity
- Reduction in turn-around times

Laser cladding process can be observed in detail in the Figure 3 below.

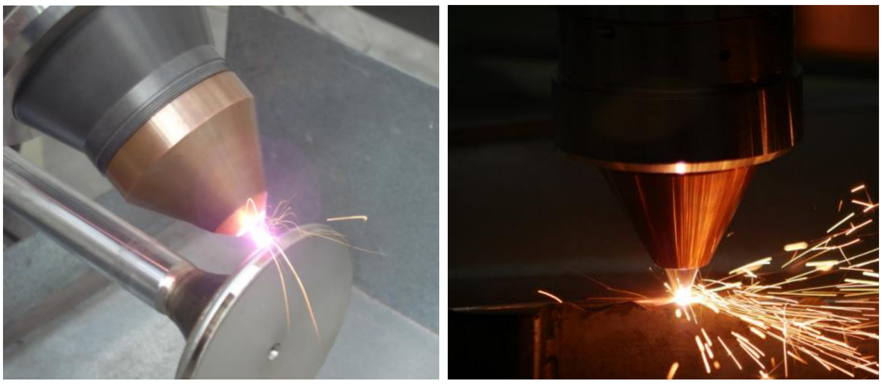


Figure 3. Laser cladding processes with coaxial powder feeding [15]

Laser cladding works using a laser beam which is established to melt the surface of the base material to a shallow depth. The clad material is then introduced in either wire or powder form and is also melted by the laser beam, thereby forming the clad layer. Besides laser cladding, overlay welding includes also traditional arc welding and electron beam welding. All these welding techniques deliver fully melted clads with metallurgical bond with high strength, good impact properties and low porosity. However, in traditional arc welding such as metal inert gas/metal active gas (MIG/MAG), tungsten inert gas (TIG), plasma-transferred arc (PTA) or submerged arc welding (SAW), the high heat input into the part usually melts too much of the substrate producing significant amount of mixing. Such dilution is undesirable because it alters the properties for which the clad material was selected, also the high heat input can cause mechanical distortion, creating the need for further processing after cladding to restore the part's dimensional accuracy. This thermal stress leads to inferior mechanical quality, surface quality problems such as cracks and porosity, as well as shortening the lifetime of the repaired part [16].

Using the laser as the heat source, offers an attractive alternative to arc welding because the laser can produce the required heating in a highly localized and controller manner. By melting very little of the bulk material, laser cladding dramatically reduces dilution in the clad layer, while still producing a true metallurgical bond. Also, the lower heat input avoids part distortion, largely eliminating the need for post-processing [16]. For these reasons, the acceptance of laser cladding by the industry is increasing.

The alloy may be introduced into the beam-material interaction zone in various ways, either during or prior processing. The type of laser used is going to depend on the surface area that will be covered, the thickness of clad required and the complexity of the component used [17].

3.2 Short arc welding (MIG/MAG)

Metal Inert/Active Gas (MIG/MAG) welding is a gas metal arc welding (GMAW) process that uses a continuous solid wire electrode which is heated and fed into the weld pool from a welding gun, joining the two base materials together or depositing a clad layer on the substrate. A shielding gas is also sent through the welding gun and protects the weld pool from contamination (MIG Welding: the basics for Mild Steel). A schematic image of MIG/MAG welding clarifying the mechanisms of the process is shown in Figure 4.

Short arc welding corresponds of a type of welding which is characterized by the fact that it is a welding with a low heat input, where the transfer of metal occurs through electrical short circuits. With the feeding of the welding wire, what is sought is to create a physical contact with the base metal and create, at the same time, a short circuit. As the shorting occurs, the voltage rapidly drops to zero. The main advantage in this type of welding is that MIG welding machines keep their voltage constant, so that there is a constant voltage in the system. To achieve this phenomenon, it is necessary to increase the amperage to break the short. Increasing the amperage generates and explosion causing splashing and a crackling noise, that can be heard while welding is carried out. This is going to happen many times per second, which is why we never see the welding arc go out [18] [19] [20].

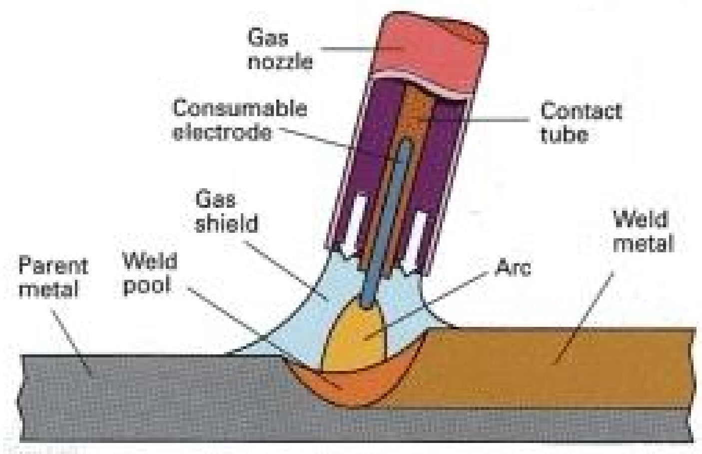


Figure 4. MIG/MAG welding process [20]

It is a versatile technique suitable for both thin sheet and thick section components. An arc is struck between the end of a wire electrode and the workpiece, melting both to form a weld pool. The wire serves as both heat source and filler metal for the joint. The weld pool is protected from the surrounding atmosphere by a shielding gas fed through a nozzle surrounding the wire. Shielding gas selection depends on the material being welded and the application.

The process usually operates with the wire positively charged and connected to a power source delivering a constant voltage [20].

3.2.1. The process of cold metal transfer (CMT)

This method could be said to be a relatively new advanced short arc welding process developed by Fronius International GmbH. It is very versatile process because it is able of fusion welding, brazing, cladding and additive manufacturing. Its main characteristic is its low heat input property, dissimilar metal welding (being able to join steel and aluminium) and nearly spatter-free welding. It is characterized by being an alternative for many types of welding or cladding methods [21].

CMT is born of the study of welding aluminium and steel which was impossible to realize with traditional welding methods. To make this possible the heat input needed would be significantly lowered. CMT process is so successful compared to traditional MIG/MAG welding due to the combination of hot and cold phases during the welding process [21].

In CMT it is possible to observe a huge variety of processes, depending on the type of material you want to be joined, or the position of the piece used in the welding process. The different variants of this process and some of their main characteristics will be explained bellow.

- *<u>CMT</u>*: is based on the wire motion. The arc disappears gradually decreasing the heat input of the process. In the first phase, the weld pool is formed, and the filler metal comes into contact with said weld pool. At this point, the arc is extinguished and the welding current decreases. This phase corresponds to the short-circuit phase. After this, the cycle begins again. The length of this cycle is not predefined, and it is showed in Figure 5.

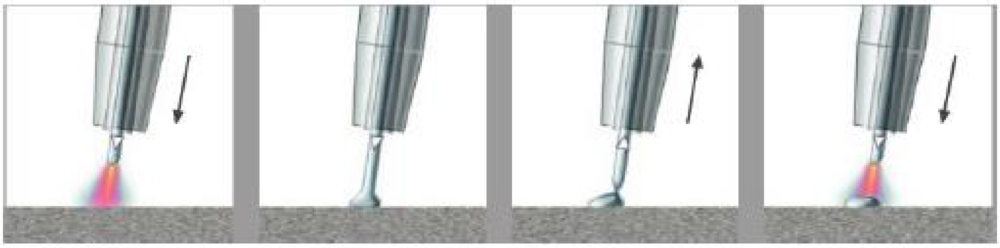


Figure 5. One cycle of basic Cold Metal Transfer process [22]

The basic CMT-process can be used widely between different types of applications, including cladding [21].

- *CMT Pulse*: in this case, a pulsed cycle is added into the process, so it is important to highlight the increment of heat input. It begins with the retraction of the wire while the arc is positive. Then the pulsed-arc phase begins. This phase consists of the movement of the wire towards the work piece while detaching a droplet. The arc is extinguished at this point and a normal CMT cycle continues again as it is showed in Figure 6.

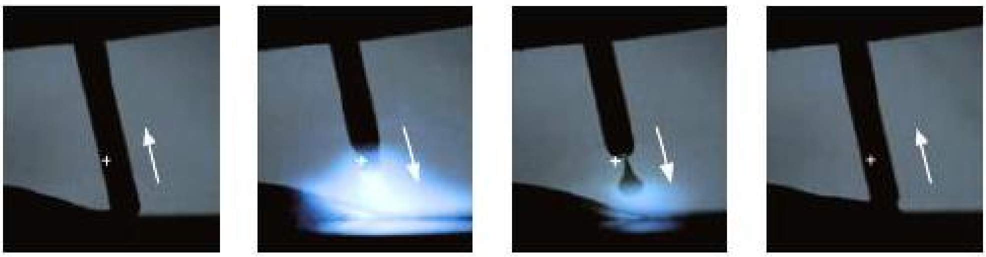


Figure 6. CMT Pulse cycle [22]

This kind of CMT gives a very narrow bead and is mainly used for aluminium welding. For cladding purpose, it is not recommended since the heat input is increased which affects the dilution and the composition of the coating [21].

- *CMT Advanced*: is the recent development in this welding technology. The process introduces alternative current (AC) into the process, combining positive and negative CMT cycles. With this new technique a much colder process is achieved than the traditional CMT process. The short-circuit phase causes the polarity reversal of the welding current [21]. This kind of CMT is observed in Figure 7.

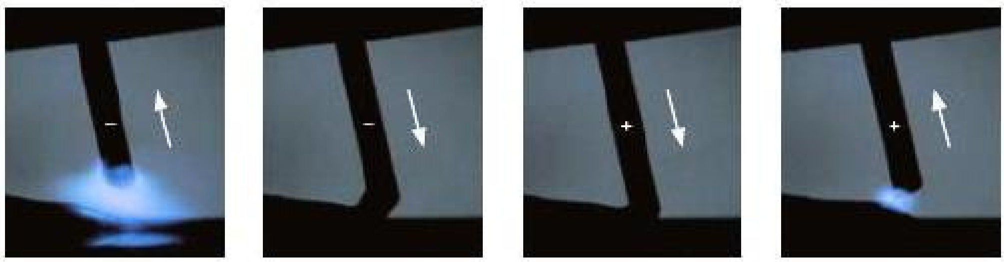


Figure 7. CMT Advanced cycle [22]

- *CMT Pulse Advanced*: in this case, CMT process combines negatively poled CMT cycles and positively poled pulsing cycles. Firstly, the CMT negative phase is present and the movement of the wire towards the workpiece takes place. It is followed by initialization phase, where the wire is retracted, and cycle is positively poled. It is continued to positively poled pulsed-arc cycles. It occurs in Figure 8.

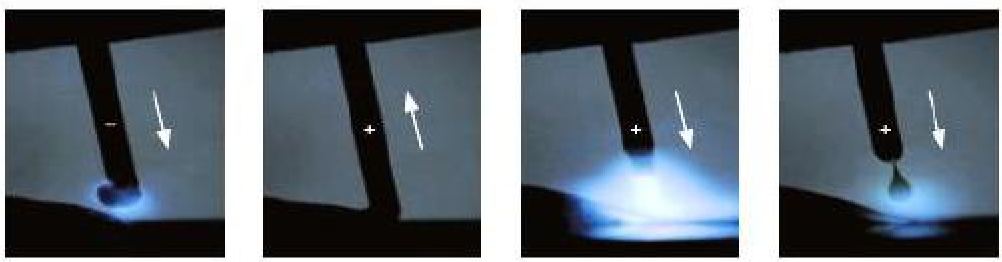


Figure 8. CMT Pulse Advanced cycle [22]

It can be observed in Figure 6, that the CMT-phase is negatively poled, and the pulses are positively poled as in CMT Pulse. The only difference between them is CMT pulse advanced which is designed for special applications [21].

- *CMT Dynamic*: this type of CMT process is the latest development in the CMT family. It has been designed in the welding of thicker plates. The to-and-fro wire movement is increased and therefore, said increase in frequency allows it to be operated by increasing the process limit. This produces deeper penetrations thus increasing deposition rates. CMT Dynamic presents more heat input, increased arc pressure and thus more energy. That is the reason for it is not design for cladding welding process [21] [22].
- *CMT Pin and CMT SynchroPuls*: these processes are designed for very specific applications. In CMT Pin, small strands of wire are welded to a metal surface. It is based on resistance heating and deposition of the free wire. It is focus on different shapes and geometries. CMT SynchroPuls combines two power ranges in a single welding process. It uses two WFR values causing a combination of both in which the two values are altered by turns. These two process phases are divided into individual CMT processes. It is used in joining applications and not recommended for cladding [21] [23].

3.2.2. The use of CMT process in cladding

CMT has been applied in the cladding of Ni-base superalloys and Al alloys. Cold metal transfer reaches deposition rates up to 5,5 to 6 kg/h with single-wire unit depending on the process parameters and the materials in question. This number is comparable to other similar overlay cladding methods. It is possible to control the dilution and penetration of the process through changes in the synergic line and adjustments in the corrections parameters [24].

3.2.3. Synergic lines

Synergic lines are one of the most important aspect in CMT-welding because they give the basic parameters automatically to each filler material and for that, it is necessary to have an appropriate program that facilitates the manufacturing of good quality welds.

Those synergic lines that contain databases should be uploaded into the remote control from computer and should be selected prior to welding. There are also more basic CMT-equipment with less automation and adaptivity, which require the user to adjust the voltage and wire feed rate. Also, due to the design of the equipment, the amount of synergic lines available is more limited.

In order to optimize the process and observe the different characteristics in more detail, synergic lines are designed with the help of an oscilloscope and a high-speed camera. Basically, a low Wire Feed Rate (WFR) value is needed to create a synergic line. To achieve this value, it is necessary to define a functioning voltage region with the help of the equipment mentioned. This method is repeated to each WFR-value until the maximum is reached.

The synergic lines can be altered with the Remote Controller Unit-controller by adding characteristic points. These modifications can be used to increase the maximum Arc Length Correction-value of a certain WRF-value to reach a higher voltage.

3.2.4. CMT-process correction parameters

When you are going to realize a welding process, it is necessary to choose the correct synergic line for the right material to obtain a decent welding result, so some parameters would usually need to be adjusted to gain an optimal result. Arc Length Correction (ALC) is used to fix the spatial elongation of the arc plasma column. With shorter arcs a favourable effect on welding speed and against undercuts is achieved, and for the formation of wide weld seam and edge formation a large long arc is needed as it has a positive effect on this. In traditional processes ALC controls the voltage and WFR, but in CMT-process the connections are more complex [10].

ALC can be adjusted from -30% to +30%. Reducing the arc length, the wire return time decreases, and the process frequency increases. When ALC has negative values, the forward acceleration of the wire increases and decreases heat input and average voltage. By increasing the arc length, the return time increases and process frequency decreases. Longer arcs lose more energy than shorter arcs, especially affecting the efficiency of the process [10].

Another important process correction is Dynamic Correction, DC. This correction simulates inductance and it is used to adjust the duration and property of the short-circuit break. In addition, DC controls the arc pressure by adjusting the reignition current and reduce the arc-force. This correction produces a higher reignition current and thus a higher arc pressure. Negative value means more penetration, so it is higher contact angle of the weld bead and more stable arc. A positive DC value is recommended for cladding purposes, but this recommendation depends on the materials [10].

Stick-out of wire has also effects on the properties of the weld, this being the distance from the contact tip to the weld pool. Stick-out changes in CMT do not affect the stability of the arc, but a shorter stick-out leads to less penetration into the base material, decreasing deposition rate. and this produces a flatter weld bead [21].

3.2.5. Advantages and disadvantages of CMT cladding

There are many benefits of CMT cladding process. The equipment is rather inexpensive when compared to other welding process. CMT has good energy efficiency and the process is flexible and capable of producing fine coatings regardless of the material. It is a cold process, which means the dilution and penetration can be controlled easily, so we can obtain good coating properties and composition. Cold metal transfer has good productivity. With twin wire systems, the rate can be doubled. There are also many different materials available with wire diameters varying from 0.8 mm to 1.6 mm covering both solid and cored wires [21].

Unfortunately, there are some negative aspects concerning CMT process, but there are not many. CMT is not as accurate dimensionally as laser system but rather thin beads can be produced with thin aluminium wire. Also, the coating thicknesses are rather high. It seems that it is not possible to manufacture 1.0 to 1.5 mm thick clad with low dilution and fusion bond. When going below this thickness area, the heat of the process is insufficient which causes defects and lack of fusion [21].

3.3 Cold spraying

Cold spray is a high kinetic energy solid-state coating and powder consolidation process. This technique uses an electrically heated high-pressure carrier gas, like nitrogen or helium, to accelerate metal powders through a supersonic nozzle above a critical velocity for particle adhesion as shown in Figure 9. The bonding mechanism is a combination of mechanical interlocking and metallurgical bonding from recrystallization at highly strained particle interfaces [25].

Cold spray can create mixtures of metallic and nonmetallic particulates to form a coating or freestanding structure by means of ballistic impingement upon a substrate. It is applicable to corrosion-resistant coating, dimensional restoration and repair, wear-resistant coating, electromagnetic interference (EMI) shielding of components and structures and field repair of components and systems.

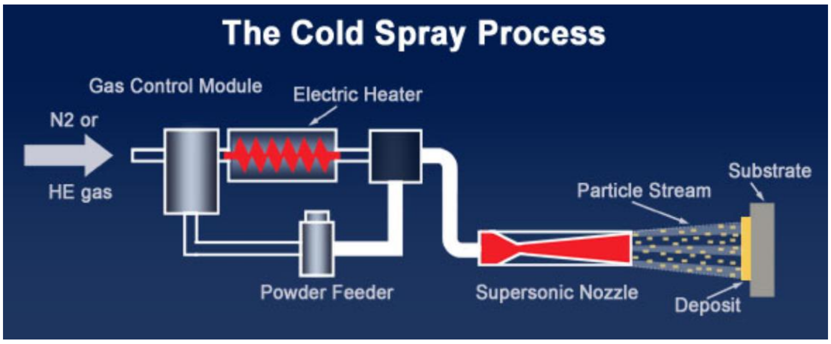


Figure 9. Schematic process of cold spraying

Benefits of cold spraying process [25]:

- Very low heat input with no ‘heat-affected-zone’
- Structural properties can be achieved
- No real limit on deposition thickness
- High deposit efficiency typically >80%
- Bond strengths >10 ksi (68 MPa)
- Coating strengths > 40 ksi (275 MPa)
- Porosity commonly below 1%
- Powder microstructure and properties are preserved
- No oxide formation, alloy decomposition, combustion product entrapment
- Compressive residual stresses in coating, rather than tensile

4. REVERSE ENGINEERING

Reverse engineering is a design process which is relative to traditional forward engineering, from sample physical to three-dimensional digital models then to final products. This method involves the integration of 3D non-contact digitization to obtain the point of the part which had been damaged, adapting free-form surface reconstruction to get the digital model of damage location and one of the many additive manufacturing/DED process containing slicing and path planning and subsequent multi-axis milling operation [26].

Some scholars have used reverse engineering techniques to study the reverse modelling of different damaged parts. Some of them present a damage reconstruction method based on tri-dexel modelling for laser-aided repairing of metallic components [27]; other applied the optical three-dimensional scanning system to obtain the point cloud data of high-strength steel sheet parts and obtained the three-dimensional model of the parts through reverse engineering through data processing [28]; another one achieved model reconstruction by combining the reverse engineering software (Geomagic studio combined with Ansys, MATLAB or UG software) [29].

At present, when the two methods are combined (directed energy deposition and reverse engineering), they become a remanufacturing technology based on both with reverse engineering aimed at restoring a part’s geometric size and optimizing the organization. Only a few scholars could combine the two methods to conduct research [26].

The literature review shows that the studies on the subsequent machining of laser direct deposition forming layer are rare in existing remanufacturing based on laser direct deposition and reverse engineering [26].

Reverse engineering of a mechanical component requires a precise digital model of the objects to be reproduced. Rather than a set of points a precise digital model can be represented by a polygon mesh or ideally for mechanical components, a CAD solid model. A 3D scanner can be used to digitise free form or gradually changing shaped components. These data points are then processed to create a usable digital model [30].

4.1 3D laser scanning

Reverse engineering is a multi-stage process, involving digitization of surface points, segmentation of data into distinctive surface regions and reconstruction of data into CAD and subsequently CAM models. Reverse engineering has traditionally used coordinate measuring machines (CMM) to digitise points on part surfaces [31].

3D laser scanning is a process which consists of analysing a real-world object of environment collecting data on its shape. With the collection data of the object, it is possible to construct a digital 3D model of the object suited [32].

This innovative kind of scanners are widely used in industrial design, engineering and manufacturing industry, due to their ability to quickly and precisely capture the required data [32].

A 3D laser scanner is a non-contact, non-destructive digital technology that captures the shape of a physical object by using a line of laser light. It creates a point cloud or a set of data points in a coordinate system that represents the exact size and shape of a three-dimensional object [33].

3D scanners measure an object's finest details, capturing free-form shapes and generating accurate point clouds for objects with complex geometries and contoured surfaces [33].

3D laser scanning is a revolution over the years, because it provides higher precision, faster scanning and better results. The entire process takes place in several steps, which we can see in detail below [33]:

- The object to be scanned is placed on the digitized bed. The laser probe is driven above the object's surface by specialized software and the probe projects a line of light onto the surface. There are two sensor cameras which are recording the changing shape and distance of the line in the three dimensions known (XYZ) while it moves along the object.

- The resulting data from this process is the point cloud. Millions of points appear on a computer monitor during the laser's movement and captures the entire surface shape of any scanned object.
- Point cloud data files are huge. After their generation, they are registered and merged into a 3D representation of the object. Sometimes, 3D laser mapping equipment is used for inspection purposes and reverse engineering to reproduce a CAD model or correct imperfections.

These considerations have led to the development of various commercially available computer vision systems, of which laser scanners are the most common. Compared to CMM touch probes, laser-based surface measurement has the advantage of speed, non-contact sensing and immediate storage of the measured data into a computer file. The primary limitations of laser scanning systems are cost and accuracy. The 3D data generated by laser-based range sensors are currently not suitable for incorporating into CAD databases or for direct CNC machining. The scanned data is irregular, unformatted, has measurement errors and requires extensive processing before the smooth and accurate reconstruction of the constituent surface patches of an object may be obtained [31].

Recently, laser scanners have been used more often for inspection and reverse engineering in such industries, as motors, electronic products, dies and molds. However, due to the lack of efficient scanning software, laser scanners are usually manually operated. In order to automate a measuring process, appropriate hardware system as well as software modules are required. The hardware system consists of a laser scanning device and setup fixtures that can provide proper location and orientation for the part to be measured. The software modules generate optimal scan plans, so that the scanning operation can be performed accordingly. In the scan planning step, various scanning parameters are considered in the generation of optimal scan paths, such as the view angle, depth of field, the length of the stripe and occlusion. The generated scan plan is downloaded to the industrial laser scanner and the point data are captured automatically [34].

4.1.1. How laser scanning system works

A laser stripe is projected onto a surface and the reflected beam is detected by CCD cameras. Through image processing and triangulation method, three-dimensional coordinates are acquired. The laser probe is mounted on a three-axis transport mechanism and moves along the scan path that consists of a series of predetermined line segments [34].

When the laser scanner captures an image, the system automatically finds an optical focus and keeps the stan-doff distance. The length of laser stripe and stand-off distance cannot be changed by an operator because the laser scanner consists of optical sensors and mechanical moving parts which have several constrictions that must be satisfied when measuring a certain point on a part [35]. This mechanism of 3D laser scanning can be observed in Figure 10.

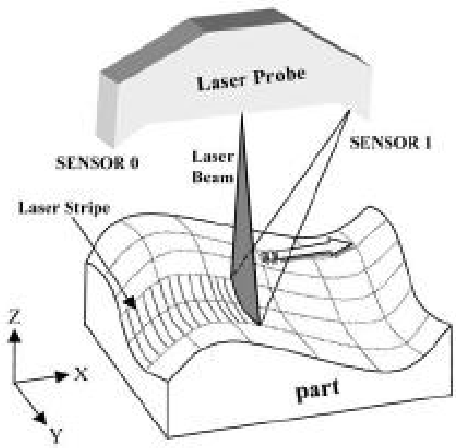


Figure 10. Laser scanning mechanism [35]

4.1.2. Procedure of scanning process

For a scan plan generation, a complex part must be segmented into functional surfaces and the scan plan will be generated for each surface path. Instead of dealing with the entire surface, the surface is approximated by a point set sampled from the surface and scanning of all sampled points by the minimum number of scans is the final goal of this algorithm.

If some points cannot be scanned, an additional direction or a modified direction is calculated according to the geometric shape of the sample. For these new directions, the same procedures are repeated until a final scan plan is generated [35].

5. REMANUFACTURING CASES

As it was discussed earlier in the section ‘2.1 Remanufacturing’, there are two different remanufacturing strategies: either change or replace the deteriorated parts with new spare parts or build the deteriorated parts back to their original dimensions with additive remanufacturing methods.

This chapter concentrates on the latter one and classifies the cases according to different industrial sectors. Because of limited information available in certain cases, these examples may include also repairing and reconditioning cases.

Remanufacturing is a recovery process that differs from other recovery processes in its completeness. This process is a transformation of an end-of-life product into a product with an ‘as good as new’ condition [36]. The meaning of this concept is that a remanufactured machine should match the same customer expectation as a new machine [9].

Remanufacturing as a product recovery operation is extensive and includes product disassembly, cleaning and identification of parts, parts recovery and products re-assembly [35]. Material recycling only occurs when the parts and components cannot be reworked.

By remanufacturing products, a company contributes to the circular economy with the main aim to extend the lifetime of those elements and creating value [10].

It is necessary to explain a concept in this field which is commonly used to understand the remanufacturing process. The (OEM) undertakes remanufacturing operations but, most commonly, the OEM collects the used products and distributes the remanufactured products through the own logistic channels. There are independent remanufacturers who are not related to the original equipment but, it is important to note that remanufactured parts are produced by the OEM [36].

It is necessary to identify the motives for remanufacturing. According to one study, profitability was questioned as one of the main motives for the OEM remanufacturer. As a result, there are some motives for remanufacturing [36].

- *Moral and ethical responsibility*: it can be considered as a motivator for product take-back and recovery. Industrial ecology theory assumes that humanity seeks to maintain (deliberately and rationally) a 'desirable carrying capacity' [37]. The concept of corporate social responsibility adds that a company is responsible for the impacts of its actions [35].
- *Environmental legislation*: at this point, it is important to say that there has been extensive discussion throughout the literature about end-on-live take-back strategies (it could read on Ref. [38]), compliances with governmental regulation (Ref. [39], pre-empting legislation (Ref. [40]) or transforming regulative pressures into a competitive advantage (Ref. [41, 42]).
- *Profitability*: belongs to so-called 'green' activities, has been questioned from various research perspectives [43]. Within this group of researches, some, even consider the question of profitability as 'obvious', yet the only obvious thing about the profitability of reverse logistics is the need for more research [44].

The typical process of remanufacturing is thorough to ensure 'like new' quality:

- Collection
- Identification and inspection
- Disassembly
- Reconditioning and replacement
- Reassembly
- Quality assurance and testing

The classification of the different cases that can appear in the remanufacturing processing are:

- Aerospace
- Oil and Gas
- Steelworks
- Tools and Moulds
- Mining
- Transportation and Engines
- Defense
- Others

5.1 Aerospace

In the aerospace industry, the huge problems are safety and performance which are the overriding concerns. Besides, repairs are highly regulated to avoid any issue in this field. It could be perceived that remanufacturing has minimal appeal. However, as the design tolerance of manufactured components is very low, the results obtained present a high percentage of defects. Due to raw materials have a high price and production processes are, typically, very complex, remanufacturing and component saving through 'transforming' could be applied in imperfect production systems to reduce the amount of scrap materials. In some cases, remanufactured components may even have longer life cycles due to thicker retread rubber [45].

To carry out the objective of remanufacture, it is important to know that this kind of industry works with a wide variety of materials, depending on the part of the airplane that is going to be manufactured. In this case, aerospace industry works with:

- *Engine parts*: Ni, CoCr, Ti and TiAl [9]
- *Fuselage components*: Al and Ti [9]
- *Undercarriage*: Ti, Al and high strength steels [9]
- *Wings and stabilizers*: stainless steel (17-4PH) and composites materials (CFRP and GFRP) [9] [46]
- *Landing gears*: Ti alloys, steel alloys and Al alloys [46]

Because of criticality of components vast certification procedures are needed before repairing/remanufacturing can be accepted, since there are different ways to realize the remanufacture process. Structural or functional parts will be repaired by laser cladding processes [47] while other parts made by metals, Ti and Al alloys and metal-based composites will be repaired by cold spraying processes [17].

5.2 Oil and Gas

The oil and gas industry are responsible of operations and engineering decision-making used in the transportation of this kind of materials through different pipes and tubes. Due to oil and gas substances are so dangerous, pipes materials should be very resistant to these chemical materials. The main issue that this kind industry can have is the corrosion, which is very important to avoid. Remanufacturing process, in this industry, is the key of avoiding the corrosion problem.

Oil and gas companies must do all they can to ensure a steady supply of product to distributors and consumers. An infrastructure of pipes that carry oil and gas across the country and around the world is essential. Parts such as piping materials, pipe shoes and wear pads, must be durable and resilient, so maintenance and repairs do not interrupt the supply of product [48].

In the oil and gas industry, we can find a huge different way to extract and transport the product through these pipes. This transport can be done both underground and outdoors system, but the deterioration of structures in consequence of corrosion has a major impact on safety, environmental conservation and, economy of pipeline operations.

In the case of these countries that do not have access to the sea, the main way to extract oil and gas is through drilling rigs. The drill is attached to the end of an extremely long hydraulic cylinder. The drill is installed, and the hydraulic cylinder pushes the drill into the earth as it turns. Once the drill is pushed as deep as the cylinder stroke allows, the hydraulic cylinder is retracted, and the next piece of steel tube is connected to the drill. Then, the extraction of oil and gas will be carried out without any danger [49].

This kind of machinery can be extremely expensive and may be taken to locations thousands of miles from its place of manufacture. Because of this, it is standard to be inspected and, if necessary, repaired or replaced every several years to ensure the perfect operation of the machinery [49].

It is important to remark the main families of materials that pipes are made of. The oil and gas industry use various materials, both metals and non-metals. More than 90% of the materials used are metals, but some of them are non-metals, especially to serve critical functions in the industry and they are increasingly replacing metals in some key areas [50]. They are mentioned below:

- *Steel*: is the most important material used in this type of chemical industry. It is a strong and reliable metal. Steel is the main material used for piping and external parts because it is strong and resistant to wear. Consequently, steel is often used with small percentages with other materials to enhance strength, durability and corrosion resistant in this type of environments [48].
- *Steel alloys*: steel, combined with any number of other materials, produces improved alloys. One of this alloy elements is chromium that helps the metal to resist the effect of carbon dioxide and hydrogen sulphide, and high temperatures. Titanium is a popular additive because of its strength and durability, but it is also resistant to a variety of substances, including seawater [48].
- *Copper and copper alloys*: they are for special within oil and gas operations. These materials are often used for valves and seals. This is due to properties like electrical and thermal conductivity that help to transfer heat and cold without warping, cracking or failing otherwise [48].

As oil and gas industry works with metal materials, the method to realize remanufacturing process will be by laser cladding [17], since that method is the most appropriate in metal materials.

5.3 Steelworks

Steelworks uses a forming process, denominated rolling process, in which the steel stock is passed through one or more pairs of rolls with the objective of reducing the thickness and to make the thickness uniform along the steel piece. Almost all the steel, cast steel being the largest exception, is produced by rolling process in a steel mill [8].

Those rolls used in hot rolling, will probably withstand high temperature oxidation, rolling contact and thermal fatigue, mechanical bending loads and abrasive wear due to hard iron oxides that are present in the rolls. Therefore, these types of rolls are often coated with heat and wear resistant coating [8].

The remanufacturing process of rolls is conducted by conventional high productivity welding methods (SAW), which leads also to high heat input into the rolls. The main goal is increasing the life cycle of steelworks rolls by developing high performance heat and abrasion resistant coatings [8].

In addition to the use of rolls, couplings are also fundamental in steelworks. In this case, couplings suffer wear, and because of that, they need to be replaced or remanufactured from time to time [8].

Finally, it is necessary to take into account that before the remanufacturing process, inspections and test procedures must be carried out, because of welding introduces residual stresses into the piece and modifies the microstructure of the substrate, being able to cause the piece to break [8].

5.4 Tools and Moulds

The tool industry provides high-skill, high-wage jobs and it has a powerful multiplier effect on the local economy, and tooling competence is critical to the competitiveness of the broader manufacturing base in a region [51].

Moulds are used to form a variety of materials such as plastic, zinc and aluminium which main objective is to design and manufacture different pieces in an industry [51]. The shape and manufacturing of tools for moulds are usually exact and very expensive [8].

In the case of tools and moulds remanufacturing, the best process would be by laser cladding, due to tools and moulds are mainly made of metal materials to allow high temperatures that they are exposed. The advantages of low heat input in this welding method are very accurate deposition of filler material in the area chosen at work-piece surface, and narrow heat affected zone in the base material [8].

5.5 Mining

The mining industry is a business full of risks, requiring substantial long-term investment. One of the main risks is the technical risk associated with project evaluation, process development, plan design, mine planning and performance of mineral processing [52].

Mining industry has had a great progress in how to extract the different minerals. Thanks to technology, the mining industry is automatized and, it is this machinery which need to be remanufactured due to the efforts it is subjected to.

Working in the mining industry requires the use of different types of machinery. These machines help achieve different mining tasks with precision and efficiency. As this kind of machines will be used in excavations, drilling, crushing large materials, earth movements and more wear works [53], it is necessary to be done of a very wear and corrosion resistant material. This is the case of steels and steel alloys, which have fantastic properties related to this concept.

In order to improve the useful life of the equipment, remanufacturing process used to repair the damage part of these machinery is by laser cladding, used for most of the parts of the machinery and, in the bucket cases, is used the short-arc welding process [17].

5.6 Transportation and Engines

Railway and rolling stock maintenance and replacement of parts is considered of the major part of the cost of running a rail transportation and a rail network [8].

Traditionally, the damaged parts of railway and rolling stock were rejected and recycled. Recently, remanufacturing process has emerged and makes by adding material. Axles and wheels are repaired with TIG and SAW, respectively [8].

As this industry needs metal alloys in their components, the remanufacturing processes used are, SAW and laser cladding [9].

Over engine industry, the combustion components are going to be subjected to different chemical and thermo-mechanical loads at high temperatures, which makes inspections and maintenance work constantly [8].

Such as the previous case, metal alloys will be used to manufacture the different pieces of combustion engine. For this reason, the remanufacturing process, in combustion engine, is made by laser cladding [8][9].

6. METHODS AND MATERIALS

Different techniques, tests and materials will be used in this thesis to obtain the main objective of the project, to be able to repair the worn part. In order to achieve that, some 3D laser scanning of worn part, welding processes, tensile tests, wear tests, basic metallography, and final inspection with 3D laser scanning will be realized which are necessary during the realization of this project. It is important to know that some different materials are used in order to study them and compare their different properties when they are subjected to the tests. The purpose of using some materials is to be able to choose the best option of repairing the studied piece.

6.1 Materials used during the tests

Materials used in the thesis consists of one base/reference material, one build-up/buffer layer material and several hard-facing alloys. Hard-facing specimens for wear tests were welded at Centria University of Applied Sciences in Kokkola, Finland, except for experimental alloy, which was welded at Tampere University in Tampere, Finland. Welding experiments with build-up/buffer layer material were conducted at Tampere University, too. This material and welding experiments are introduced later in section 6.2.2.

6.1.1. Case-hardened steel

Firstly, the reference material, which the worn part is made of, is introduced. This material is a case-hardened steel, specifically 18CrNiMo7-6 steel. Its surface hardness is about 700 HV up to 1 mm depth. Hardness in deeper is 400 HV. These properties are going to be confirmed when measuring the hardnesses from the polished cross sections. Its typical chemical analysis is shown in Table 1.

Table 1. Chemical analysis of 18CrNiMo7-6 steel in wt.% [54]

MATERIAL	WEIGHT PERCENTAGE (%)
Carbon	0.18
Silicon	0.20
Manganese	0.70
Chromium	1.65
Nickel	1.55
Molybdenum	0.30

Carburised and heat treated it develops a hard wear resistant case to HRC 60-63 and a tough strong core with a typical tensile strength range of 900-1300 MPa, in small to large sections [54]. The typical mechanical properties of this material can be observed in Table 2.

Table 2. Mechanical properties of 18CrNiMo7-6 steel [54]

Section (mm)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Impact Izod (J)	Hardness (HB)
25	1050	1295	14	45	380
50	950	1160	15	51	340
100	815	1010	16	53	300

About welding, it can be readily welded in the annealed condition, but it is not recommended to weld it in the case hardened or through hardened condition. The use of low hydrogen electrodes is recommended. It is important to pre-heat the sample at 250-350 ºC before welding process and maintain during welding [54].

CMT method is used in this thesis to weld this type of material. First, build-up layer will be welded on case-hardened steel in hardened condition (~400 HV) using a high-strength low-alloy (HSLA) steel welding wire after which the hard-facing layer will be welded on top of HSLA layer.

6.1.2 NiFD Plus

This material is a Ni-based alloy with spherical fused tungsten carbide (FTC) reinforcements for obtain the highest wear protection. It is a pseudo alloy with a matrix of nickel and a low share of boron as well as large, embedded FTC particles to offer a high degree of protection against abrasion and erosion [55]. In the next Table 3, it can be observed the chemical analysis of this material.

Table 3. Chemical analysis of NiFD Plus in wt.% [55]

	NiCrBSi	FTC
NiFD Plus	40	60

For this work, it will be used two types of samples of this type of material; one of them CMT welded at elevated working temperature of 300 ºC, and the second one at room temperature.

6.1.3. FeV12LC

This Fe-based hard-facing alloy has a reduced carbon content. FeV12LC is a cored wire electrode for gas shielded arc welding, which deposits a tough, martensitic-austenitic structure with finely divided in-situ synthesized vanadium carbides. The alloy is used to armour machine parts that are exposed to heavy wear and tear, as well as rubbing wear [56]. Table 4 shows us the chemical composition of the material.

Table 4. Chemical analysis of FeV12LC in wt.% [56]

C	Si	Mn	Cr	Mo	V	Fe
2.5	0.5	0.2	7.0	1.2	10.0	Basis
3.0	1.0	0.6	11.0	1.6	13.0	

6.1.4. Drill Guard hardfacing Ti

Drill Guard hardfacing Ti is a unique Fe-based hardbanding wire that offers superior protection with excellent welder appeal and a high level of compatibility with other competitive hardbanding products. This kind of material has been developed for the oil and gas drilling industry to offer maximum wear protection to both drill-pipe and casing. It contains titanium, vanadium and niobium carbides [57].

6.1.5. Experimental

The fourth hard-facing alloy is the experimental flux-cored welding wire consisting of Fe, C, Cr and Mo reinforced with coarse vanadium carbides.

6.2 Methods used during the project

During the realization of this project, some different tests have been done to the samples to study the behaviour of these materials under different working condition.

6.2.1. 3D laser scanning

The equipment used in this practice is Hexagon HP-L-20.8 (Hexagon Manufacturing Intelligence, Cobham, UK). It consists of a portable measuring arm which has a laser scanner and it is connected to a computer, which has a Polyworks 2017 (InnovMetric Software Inc., Quebec, Canada) software with the main goal of modifying the dimensions of the specimen or detecting the damage of the part be able to repair it. This gun is used to obtain the digital image of the specimen, since the laser captures the shape of the object scanned getting its digital image into a computer, where it can be studied and modified as a virtual piece to carry out its remanufacturing process.

In the initial part it is very important to scan the piece carefully, because the presence of holes in the simulated piece during the scanning process is not recommended, since the presence of these holes it is more difficult to carry out the rest of the remanufacturing process. For this reason, we had to make several passes with the laser gun so that the piece looked complete on the monitor. Once we had the piece completely scanned, we could continue with the 3D laser scanning programme.

The programme is a useful tool in the project, in order to improve the methodology of remanufacturing process. With this 3D programme, we focused on the damaged part trying to obtain the measures of it with the objective of build-up the damaged part to back to the original dimensions.

6.2.2. Welding process

Regarding build-up layer, CMT process is used to realize welding with HSLA wire (Union NiMoCr) in the longitudinal direction on top of S355 construction steel. The main idea of this part is to check the welding parameters before conducting welding on case-hardened steel by cutting that longitudinal weld in transversal direction to carry out a metallographic study and study the properties of the weld cut.

NiMoCr wire used, has a diameter of 1,2 mm and a copper-like colour, which is shown in Figure 11. This characteristic colour originates from a thin layer of Cu with the objective of the material to slide much better and make better contact with the contact tip of the welding gun. NiMoCr wire is a low-alloyed solid wire electrode for shielded arc welding of quenched, tempered and thermomechanically treated fine-grained structural steels. According to a standard EN ISO 16834-A, it is classified as G 69 6 M21 Mn4Ni1,5CrMo. It is recommended for using with CO_2 and gas mixture. NiMoCr wire presents an outstanding toughness of the weld metal at low temperatures and it is used in crane and vehicle manufacturing [58]. The mechanical properties are observed in Table 5.

Table 5. Mechanical properties of NiMoCr [58]

Heat-treatment	Shielding gas	Yield strength $R_{p0.2}$	Tensile strength R_m	Elongation A (L_0=5d_0)	Impact work ISO-V KV J		
		MPa	MPa	%	+20 °C	–40 °C	–60 °C
aw	CO_2	680	740	18	80	47	
aw	M21	720	780	16	100		47

Figure 11. Wire of NiMoCr

Before starting the welding, it is necessary to install the wire spool in the equipment. After that, the wire is inserted through a Teflon tube liner, to introduce it into the welding gun. Then, the synergy line is selected from the remote-control unit. In this case, it is a MIG/MAG synergic welding, which filler metal material is G3Si1. The next step is selecting the diameter and type of gas used during the welding process. At this point, it is important to know what type of gas is used in the process, because there are many options. Our best option is, according to the standard of the NiMoCr material, a mixture of gases (M21 Ar and 18% of CO_2). The next step is choosing the wire feed. In our case, the wire feed will be 5 m/min, because the higher wire feed, the productivity would be better. In the next image (Figure 12) is possible to observe the CMT robot used during this process.

Figure 12. CMT welding robot

The plate where the weld is going to be done, Figure 13, is made of S355 material. It is important to ensure of cleaning the surface of welding to avoid any type of contamination in the sample in the later study. In order to do that, the plate is going to be cleaned by ethanol and by grit-blasting. Once we had the sample and the welding robot in the desired position, arc and shielding gas is going to put on.

Figure 13. S355 sample ready to be welded

When the first single bead welding was done, the width of the weld bead was measured. This measure is 6 mm of width. In order to weld multi-beads side by side with overlapping rate of 50%, inter-track advance of 3 mm was programmed to the robot. At this point, we also changed the number of beads from one to three.

The next step is to do some welding but with different penetration in the sample. To do that, it is necessary to change, in the command of the welding machine, the arc length correction parameter (ALC). We select -15% as ALC parameter which means that the penetration will be lower, and the process colder. The result of the welding process is observed in Figure 14, where the different welding beads can be seen and, each of these welding beads present the different conditions said before.

Figure 14. Final welding process. Bead length is 150 mm

The second time the experiments were done, the sample was case-hardened steel (Figure 15). As it was mentioned previously, this type of material must be pre-heated before proceeding to the welding process. Pre-heating of 250ºC was used.

Figure 15. Case hardening samples used in welding process

In this case, the welding process was conducted layer by layer. First four layers in total for initial test and then, later 39 layers in total to build the deposit from where to extract tensile specimens for adhesion test. These layers were done with bi-directional movements.

The travel speed is 10 mm/s, and the most important thing is the weave-width. With a weave width of 2 mm, the width of welding bead is 5 mm. This value is too small, because we want it to be 6 mm, so it is necessary to increase the weave width value first to 4 mm and then later to 6 mm.

The total height value of four-layer deposit was 7 mm. The objective of this final value is calculating the height of each layer, which is 1,75 mm of height. These calculations are needed to adjust height increment in welding of 39 layers. The deposit with 39 layers is shown in Figure 16.

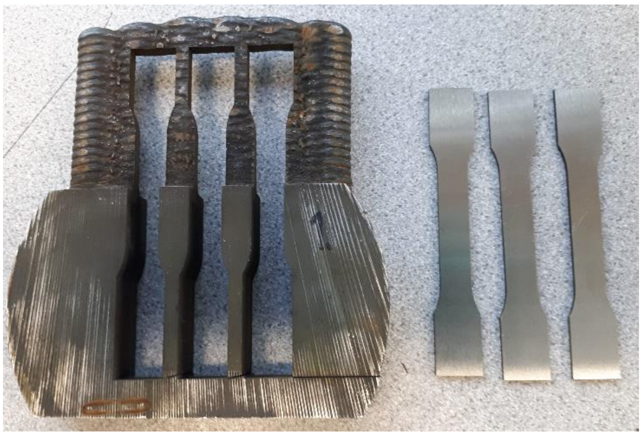


Figure 16. Tensile specimens

6.2.3. Wear tests

Wear test (high-speed slurry-pot type erosion tester) is a test which measures the wear resistance of different materials for mining and dredging pumps. This kind of experiments are made in dry condition.

Demanding industrial wear problems cannot be properly simulated in the laboratory with standard methods used. The main reason is that most of the commonly available testing methods are based on low-stress wear condition, while in mining high-stress wear conditions dominate. For this reason, several wear testers that can also utilize large sized abrasive particles to produce high-stress wear. It is important to note that in high-stress wear conditions work hardening can almost double the hardness of the wear surfaces, thus in general also increasing the material's wear resistance [59].

During this part of the project, CMT clad hard-facing alloys and case-hardened steel are used in the tests. The main objective to do that is comparing the lost mass of each material and can choose the best option to use in the remanufacturing part of the project. The material with the least loss of mass will be the one with the best resistance of wear present.

In order to achieve the main objective of this test, it is necessary to put the samples in the wear machine, but the samples will be put in the machine at 90 degrees angle to ensure the maximum impact and abrasion in the desired face of sample. Two samples at a time will be positioned in the second hole from the bottom part of the tube. The wear machine is going to rotate counterclockwise. The next images show the samples in the dry pot machine.

Figure 17. How the samples are positioned in the dry pot test

Since this test consists of abrasion, it is necessary to use some different abrasives to do that. Firstly, NILSIÄ Quartz abrasive with particle size of 0,1-0,6 mm was spread on the bottom of pot. The amount of this material was 1,350 kg.

Figure 18. NILSIÄ Quartz in the wear pot

Once the NILSIÄ Quartz was loaded in the pot, the lid was closed and the second abrasive, Kuru granite was added to the pot. Kuru granite has a bigger particle size, 8-10 mm, and the amount of that is 8 kg.

Figure 19. Kuru granite particles used

Before filling the pot with the abrasives, the wear specimens were weighed 3 times with a precision scale.

The total time of this test is 1 hour, but it is divided into two processes of 30 min each. The first 30 min, one sample is put into the yellow part of the wear machine while the other one is on the other part. After this 30 min, the test is stopped, the specimens are weighed, the pot is filled again with the two materials mentioned previously and the test started again; but this time, the sample which was in the yellow part will be changed by the other one, in order to the abrasion is done in both positions. Finally, after the last 30 min, the test is stopped, the samples measured again, and the pot machine cleaned.

6.2.4. Tensile tests

A tensile test is one of the most fundamental and common types of mechanical testing. It applies tensile force to a material and measures the specimen's response to the stress. By doing this, tensile tests determine how strong a material is and how much it can elongate [60].

By measuring the material while it is being pulled, a complete profile of its tensile properties can be obtained. A plot is obtained, which present some data results shown in a stress-strain curve. That curve shows how the material reacted to the forces being applied. The point of break or failure is of much interest, but other important properties include the modulus of elasticity, yield strength and strain [60].

In the tensile test, the specimen is subjected to an increasing uniaxial tensile load. As the test proceeds, the applied load and the elongation experienced by the extensometer, which is placed in the test piece will be recorded. It is important to know that the tensile specimens must be standardized, according to for instance EN 10002-1 standard [61].

According to this test, the equipment used, in this case, was Instron 8801 servohydraulic testing system (Instron, Norwood, CO, USA), which is shown in the figure below, Figure 20.

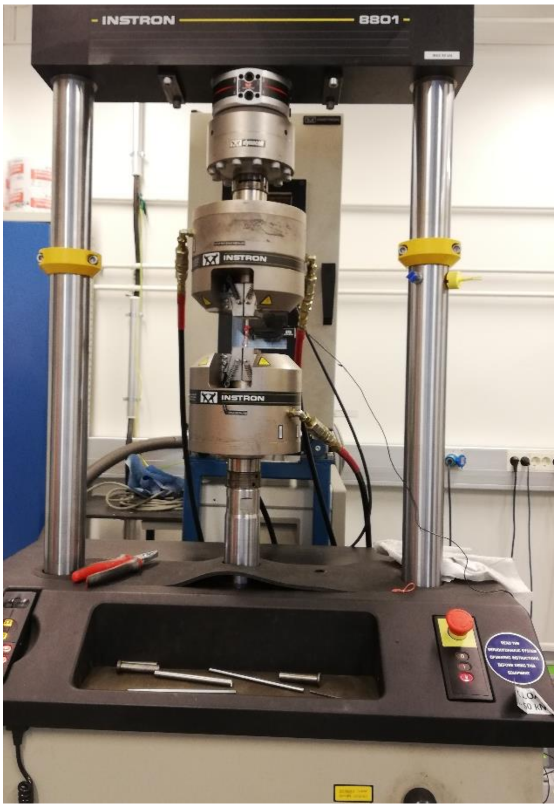


Figure 20. Tensile testing machine used in the process

6.2.5. Metallographic preparation

Starting with the metallographic preparation, it is necessary to cut the samples with a cutting machine. To do that, a specific cutting disc will be used for each sample depending on how hard the piece to be cut is. Almost all samples have a similar hardness, so the 56A25 disc will be used for these pieces, but the sample named PLUS has a greater hardness and the disc used will be 60A25 instead of 56A25 disc. The machine used during the process is shown in the Figure 21.

Figure 21. Cutting machine used in metallographic process

Once all the pieces are cut, the next step is mounting the different samples to be able to be observed in the microscope and realize the hardness profile before.

In our case, mounting the pieces will be made by hot mounting process where the specimen is placed in a mounting cylinder in a hot mounting press, and the appropriate mounting resin is added; Polyfast resins are used in our project. Then, a temperature around 180ºC and a force of about 250 bar is applied during the embedding of the specimen. The last step in mounting process is the cooling by water [62].

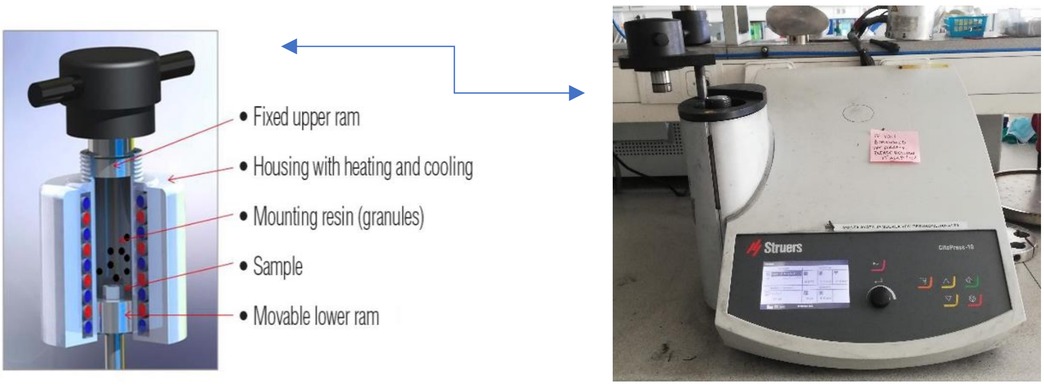


Figure 22. Hot mounting machine used

Polyfast resin corresponds to a thermosetting resin which are cured at elevated temperatures. To avoid porous, non-uniform mounts, it is important that the pressure is always constant [62].

In the next images, it can be observed some samples with the mounting process done.

Figure 23. Samples with mounting process done

When the samples are mounted, the next step is grinding part. In this part, some different papers will be used in order to remove the resin residues that may be on the surface of the piece to be tested, and polish said piece, to be able to perform hardness and metallography. The grinding part will be made manually, and the sample will be ground in a different direction on each paper used, with the aim of removing the marks created by the grinding, called scratches, and obtaining the appearance of the mirror.

The first disc will be used to remove the resin residues of the surface of our piece. The disc is named 240 paper, which present a grain size of 68 μm. The next one will be 320 paper with a grain size of 46 μm. The next disc will be 600 and its grain size is 30 μm. Then, 1200 paper is used and the grain size of this one is 15 μm. The final two discs are 2000 paper with 10 μm of grain size and, finally, the 4000 paper, which has 5 μm of grain size. It could be observed that the size of the grain is decreasing. It is because the objective is to obtain an increasingly fine grinding.

Figure 24. Some samples with grinding part one

The final step in chemical laboratory is polishing. This part consists of obtaining the mirror appearance on each of the pieces, because with this last step, it is possible to observe the microstructure of the pieces under a microscope.

Polishing method is similar to the previous one, but in this case, cloths will be used instead of discs. Three cloths are used to achieve our objective. Each of the cloths use a specific abrasive particle suspended in a lubricant that will be sprayed across the cloth. The specific abrasive will have a different size of particles, depending on the cloths used.

Figure 25. Grinding and polishing machine

The first cloth, DiaProDac, uses an abrasive of 3 μm size of particle. Once the piece has the appearance desired, it is important to clean up with water and then with ethanol to avoid the appearance of corrosion elements on the surface of the piece polished. This step, cleaning step, it is carried out with all the cloths, once we have finished with its use. In this first step, the scratches produced during the grinding part will be removed. The next one, NAP-B, uses particles of 1 μm size and the last cloth, NAP, uses the smaller size particles, ¼ μm.

To continue with the project, the next step in the metallographic part is realizing the hardness profile to each of the pieces. In our case, Vickers hardness will be used to measure this property of the material. For the load applied in the test, 1 kg is necessary to apply, and the indentation is automatic.

Finally, the last step in this chapter is the microscopy. An optical microscope is used in this part. The main objective of this step is to identify the area where the both materials (base material and coating material) are joined by the welding process and observe the cross section of the piece.

7. RESULTS

7.1 3D laser scanning of worn part

Worn part was 3D laser scanned and compared to the original 3D CAD model of the part in order to define the amount wear and how much pre-machining is needed before building the part back to its original dimensions. The original and scanned edge of the worn part area are shown in Figure 26. Comparison of scanned edge and edge of the original part is displayed in Figure 27 allowing to define the amount of pre-machining and production of replica pieces, which were later used in welding experiments to build the part back to its original dimensions.

a) b)

Figure 26. An edge from the a) original and b) worn part

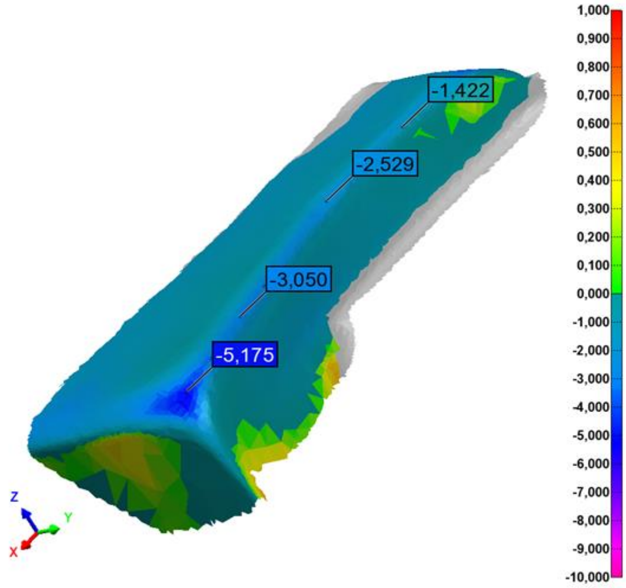


Figure 27. Comparison of a scanned edge and an edge from the original piece scanned

7.2 Metallography

Cross sections of CMT welded filler alloys, hard-facing alloys and reference materials are depicted in the images which can be seen in the next sections. Some images of the cross section were taken with different magnifications to be able to observe a better resolution of the area studied.

7.2.1. HSLA steel (Union NiMoCr)

Cross section of CMT welded bead can be seen in Figure 28. There are three crack-free beads side by side with negligible dilution. One inter-run pore can be observed at the clad/substrate interface.

Figure 28. Cross section of CMT welded beads

7.2.2. NiFD PLUS SAMPLE

Two images are shown of this sample, one of them at 2.5 magnification and the other one at 5 magnification, to observe better the differences into the microstructures.

The black area of the image is corresponding to the resin material used during the mounting process. The coating material is in the upper part of the imagen shown below. This area presents big globular particles that are very characteristic of its microstructure. They are primary WC/W_2C carbides ranging between 5 and 160 and averaging 44 μm in size. Their volume percentage is approximately 37 %. In the image, it is possible to observe the hardness profile made in this piece. If you follow the hardness profile and go down in the image, the base material is observed. In this bottom part of the sample, it can be appreciated the difference in the microstructure of the sample. In this area, the microstructure is quite different with respect to the coating material. This base material has a much more homogeneous and smoother microstructure. For that reason, its hardness values are lower than the hardness values of coating material, which are the highest one. However, there is a small zone where the hardness values are between the values of the both materials. This fine line corresponds with the interface area.

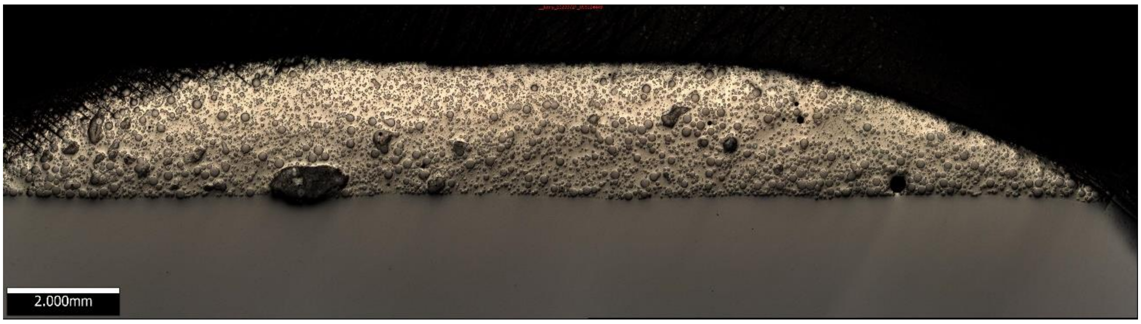


Figure 29. PLUS Sample at x2.5 magnification

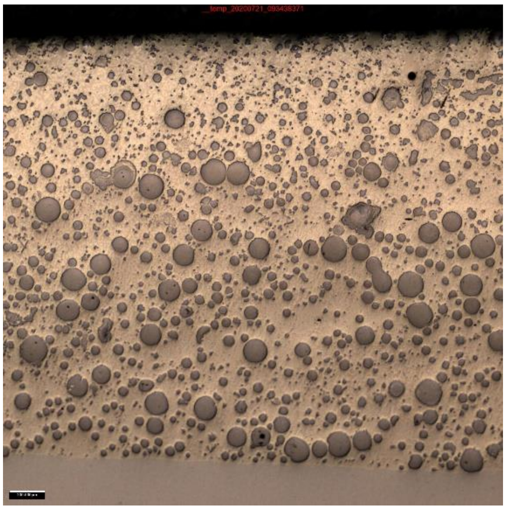


Figure 30. PLUS Sample at x5 magnification

The hardness profile corresponding to this sample, is seen in the figure below. Hardness profile was done from the upper part of the coating material to the bottom part of the base material, going through the interface between the two materials. Step between indentations in coating and in substrate is around 0.8 mm. The measurements approximately to the depth of 1.5 mm below the substrate surface.

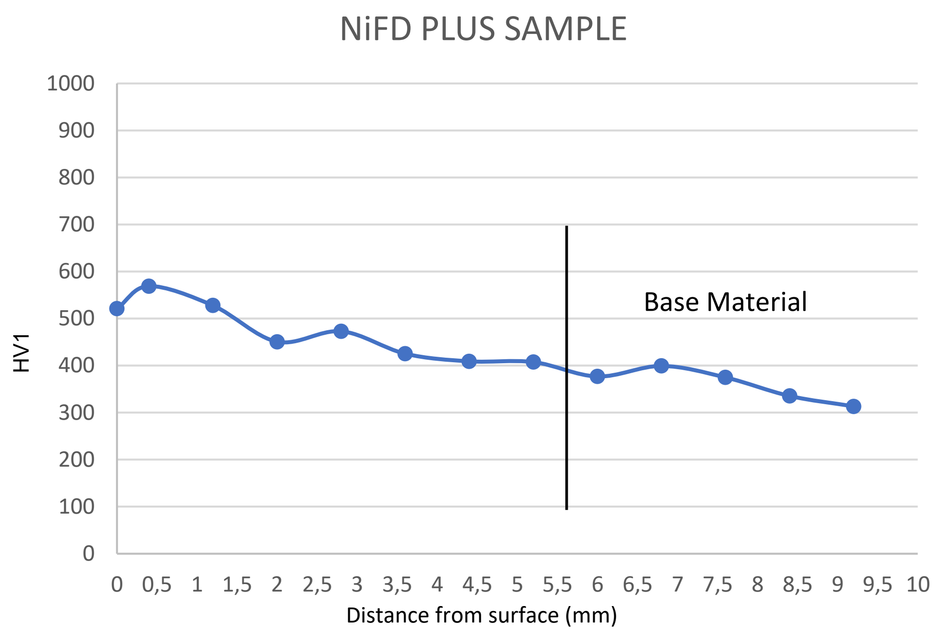


Figure 31. Hardness profile of PLUS Sample

7.2.3. Fe12V SAMPLE

Such as in the previous case, the picture taken shows a corner of the piece where you can see the part of the resin where the piece is embedded, the coating material and the material base.

In this case, both microstructures, coating material and base material, are quite similar, being very difficult to differentiate them. With this piece, the interface line was almost unappreciated. It can also be seen that there are vertical cracks in the coating material. The geometrical dilution is 12.5%.

Hardness values of the upper part of the sample present the greatest, while in the substrate part, the values are lower. It is curious how decreasing the hardness values in the interface area, being these values much lower than the coating material, but some higher than the base material.

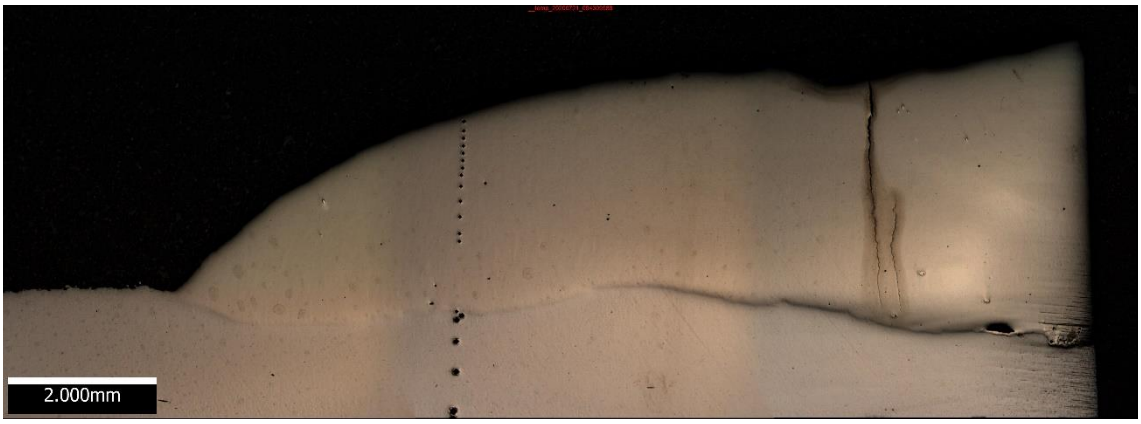


Figure 32. FeV12 Sample at x2.5 magnification

The hardness profile corresponding to this sample, is seen in Figure 33. Hardness profile was done from the upper part of the coating material to the bottom part of the base material, going through the interface between the two materials. In this case, some hardnesses were made to be able to see the difference in hardness between the two joined materials, because it was very difficult to find the interface area. In this hardness profile, the step between indentations in the coating part is about 0.25 mm while the step between indentations into the substrate part is 0.8 mm. The measurements approximately to the depth of 1.5 mm below the substrate surface.

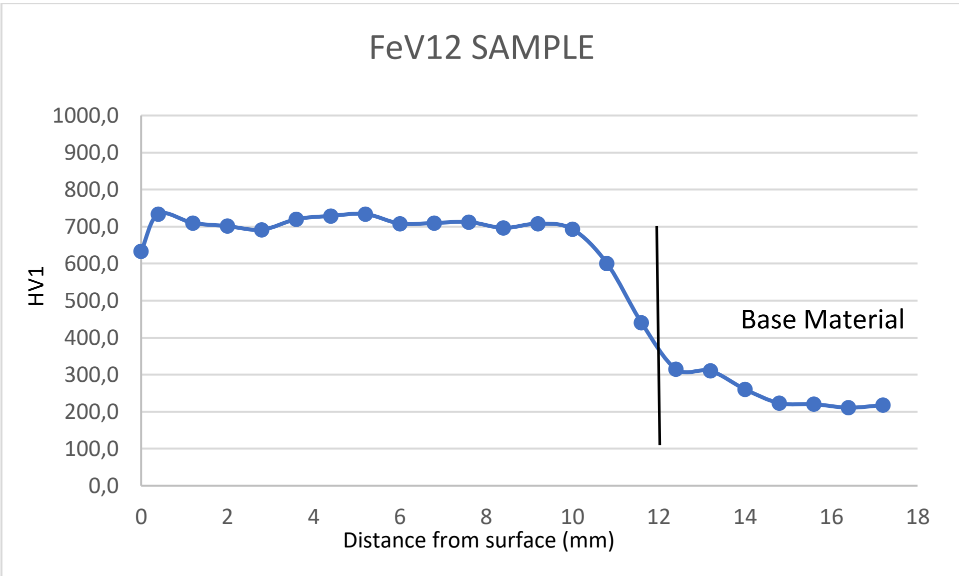


Figure 33. Hardness profile of FeV12 Sample

7.2.4. DRILL GUARD SAMPLE

In the analysis of Drill Guard sample, some images were taken of different parts of the sample. In some of them, it can be observed the coating material, the base material and the resin part of the mounting. Unlike the previous sample, in this case the microstructures are very similar to each other, and you can see the direction which the welding has been made, in the case of coating material. It can also be seen that the coating is heavily diluted. The geometrical dilution of the coating is 38%.

The microstructure of the coating material has a sponge-like appearance, as it has numerous very small holes along the material, which are pores. On the other hand, base material has a smoother microstructure without holes.

The fact of the presence of micro holes in the microstructure has that its hardness will be higher and, when you realize the hardness profile along the sample, it can be seen how the values decrease, being the lowest one in the base material part.

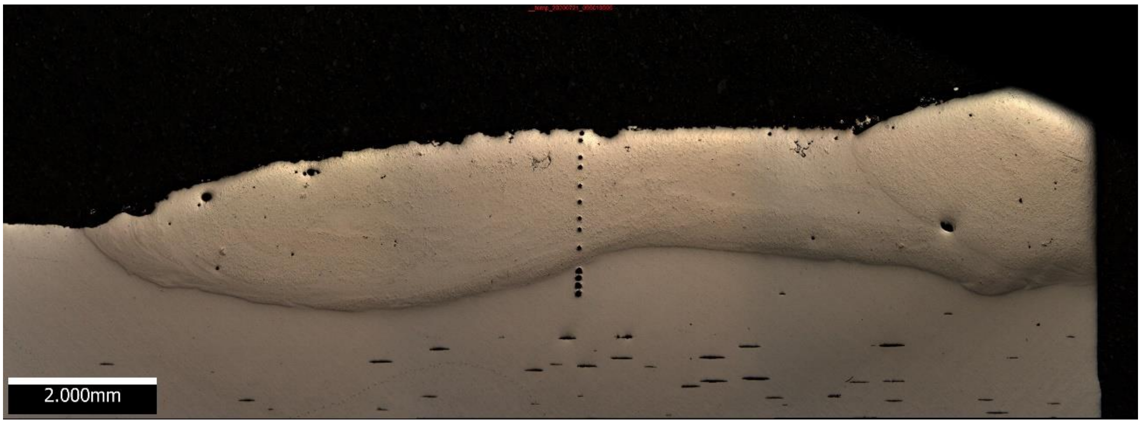


Figure 34. Drill Guard Sample at x2.5 magnification

The hardness profile corresponding to this sample, is seen in the image below. Such as the last case, hardness profile was done from the upper part of the coating material to the bottom part of the base material, going through the interface between the two materials.

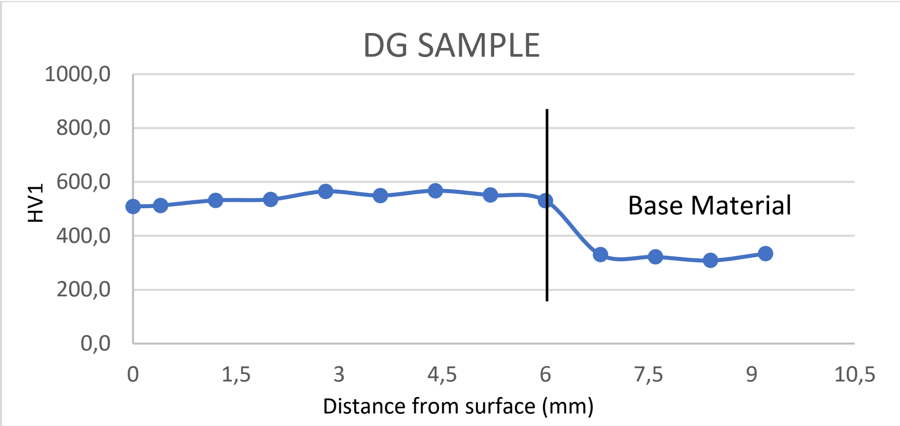
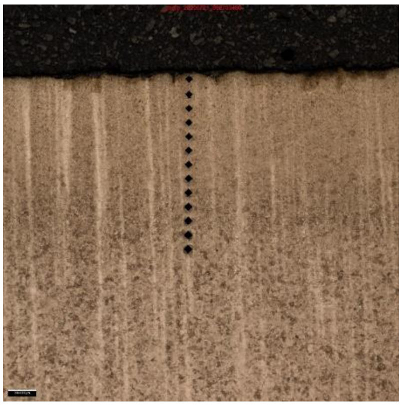


Figure 35. Hardness profile of Drill Guard Sample

7.2.5 CASE-HARDENED STEEL SAMPLE

The analysis of this piece is carried out in the same way as the previous one. In this case, the image shows us the cross section of our sample, where the Vickers marks can be observed. This case is quite different than the other cases because in this material there is no coating at all. It just has the hardened layer on the top of the sample where the carbon content is higher than deeper in the steel. For this reason, it took some pictures of the hardness marks where it can see how the footprints produced by the durometer are different depending on the type of material in which they have been made. In the hardened layer, the Vickers diamond footprints have left no marks around them caused by the pressure exerted by the durometer. This means that the material in which we are taking measurements corresponds to a hard material whose hardnesses are high. On the other hand, when these traces are observed in the bottom part of the image, there are certain marks around the footprints. This would correspond to a much softer material whose hardness values are lower. This part of the material is the base material. Case-hardened steel was etched to be able to observe their microstructure better.



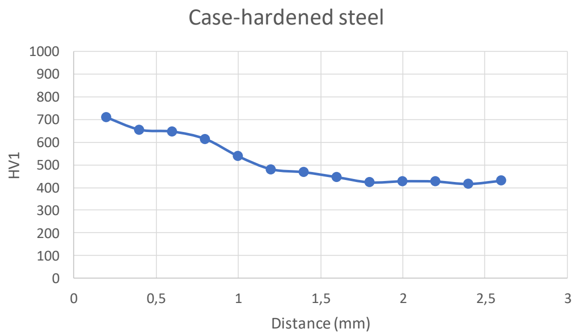


Figure 36. Case-hardened Sample etched at x5 magnification and hardness profile

The hardness profile corresponding to this specimen is seen in the Figure 36. Such as the last case, hardness profile was done from the upper part of the hardened layer to the bottom part of the base material, going through the interface between two both materials.

7.2.6. TENSILE SPECIMEN

In order to study this piece, some aspects have been considered. Firstly, the images were taken did not show the microscopy at all, so using an etching technique was necessary. This had to be done since, when watching at the microstructure of the sample under the microscope, almost nothing could be distinguished. With etching process, what is achieved is that it reveals the microstructure of the sample, and thus be able to do a study on it.

Etching is a chemical process used after metallographic grinding and polishing processes. This technique exerts a controlled influence on the surface profile or optical properties at grain boundaries, phases or grain surfaces, enabling microscopy inspection and additional use of optical filters in the microscope [63].

The etching process carried out with this piece was chemical etching which consists of the complete immersion of a prepared sample into an etching fluid [63], in our case the fluid used was 4% NITAL acid, Figure 37.

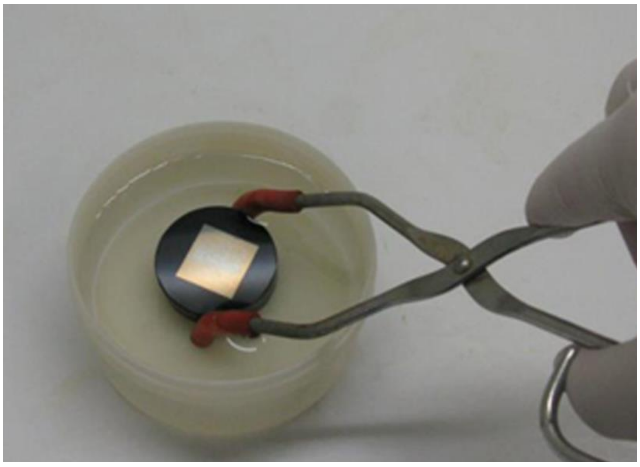


Figure 37. Chemical etching carried out on Tensile Sample [63]

After etching, some images, at different magnifications, were taken to observe its microstructure and how the hardness values changed along the specimen. Here we are going to differentiate two very different parts, one of them corresponding to the coating material and, the other one, to the base material. In both sides, some marks can be observed. These marks correspond to the hardness profile.

In this sample, a lot of hardness values were made because we observed a dividing line between the two materials, corresponding to the interface, and we wanted to check whether the hardness values varied along said line and on both sides of it. Indeed, it was possible to verify that along the line the values were very similar to each other, while on both sides of the interface, the values varied considerably. Those values of grater hardness collected by the hardness tester correspond to the interphase of the piece; on the other hand, on both sides you will have much lower hardness values corresponding to the softer material.

Figure 38. Tensile Sample at x2.5 magnification

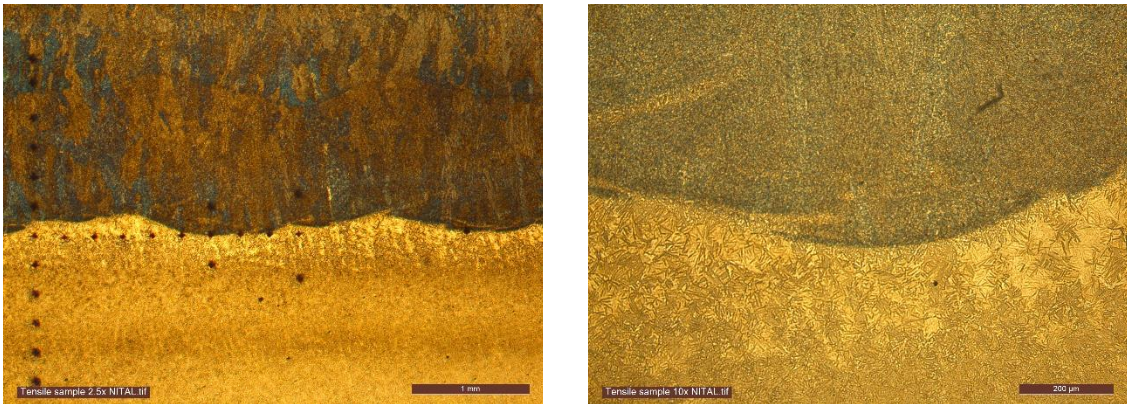


Figure 39. Tensile sample with hardness profile at x2.5 and x10 magnification

Hardness profile was made along the sample, forming a square figure with the main objective of analyzing the main parts of the piece. This hardness profile is seen in the Figure 40.

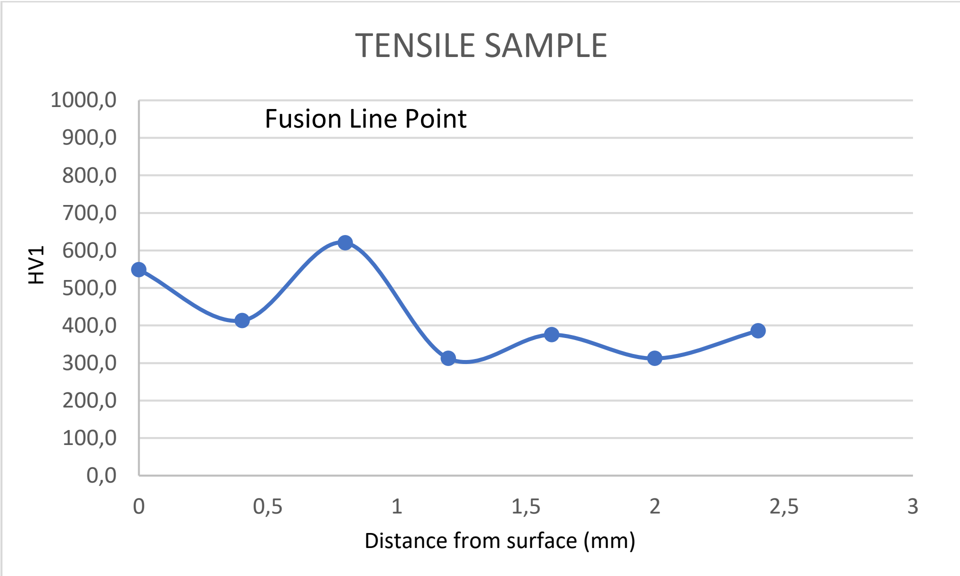


Figure 40. Hardness profile of Tensile Sample

7.3 Wear test results

Wear test results are seen in Figure 41. In this chart, weight loss of pieces is observed. There is one of the pieces, case-hardened steel, that is a wrought steel and, the rest of the pieces are made by CMT process.

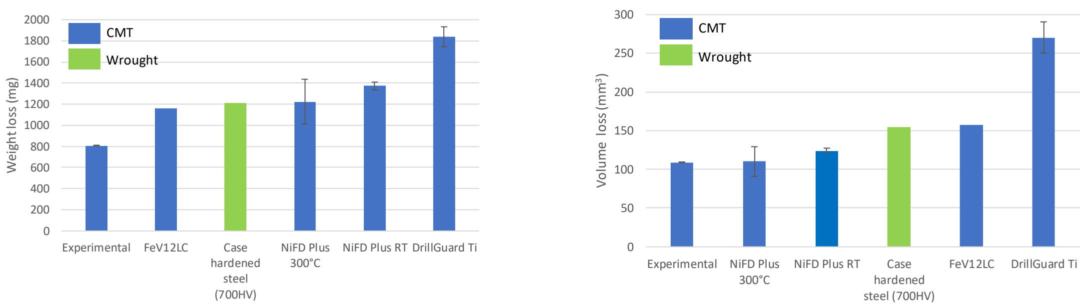


Figure 41. Wear test results (weight and volume loss)

Experimental wire (Fe-base hard-facing alloy reinforced with coarse Vanadium carbides) exhibits the lowest mass loss. It can be observed that the results change a bit depending on its different densities of the materials used in the study.

Based on volume losses, the best materials are “experimental” and NiFD PLUS samples, which volume loss result is more relevant than mass loss, are outperforming case-hardened steel, which is the current material.

7.4 Tensile tests

Tensile test results are shown in Figure 42. All the specimens fractured from the weldment side because this part of welding has the lowest strength.

Heat affected zone (HAZ) is provoked by welding process. In our specific case, HAZ is formed in the case-hardened steel beneath the first clad layer. This zone is formed also in each clad layer due to the heat provided by the next layer. When a welding is realized, microstructure of the piece is modified by heat applied during the welding process in HAZ zone, near to weld. For this reason, this part of the piece may be the weakest zone and tends to break more easily when a load is applied to, but this phenomenon in the clad layer has to be confirmed by making metallographic samples of tensile test specimen.

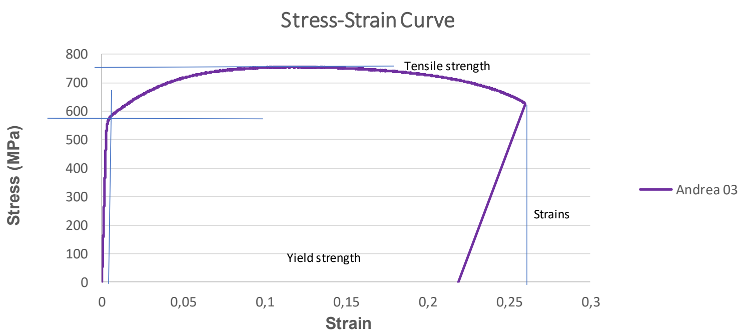


Figure 42. Fractured specimens by tensile test and Tensile test results

In the stress-strain curve it is observed how is the behaviour of the material when a load is applied to. It is important to highlight that this curve is an average of all the curves plotted. As it can be observed, some important information is given of the pieces tested. We can observe the maximum value of yield strength, 610 MPa, which corresponds to the point of the curve where the material begins to have a plastic behaviour, ceasing to be elastic. From this point, the material will never return to its initial shape.

Tensile strength of material is also observed. In this case, the average value of tensile strength is 746 MPa. Besides, the elongation at break is also observed. The value of this property is 23.6%. Meaning of this value is that the material is able to lengthen, before breaking, 23.6% of its longitudinal dimension.

These adhesion tests proved that HAZ in the base material or fusion line of it are not the weakest zones. Mechanical properties of the weldment is the weakest zone, which can be improved by choosing higher strength welding wire, for instance from the class G79 or G89.

7.5 Final Inspection

Pre-machined replicas were finally welded and inspected with a 3D laser scanner. They are shown in Figure 43. The welded replica consisted of three layers of filler alloy and one layer of hard-facing alloy. Comparison of pre-machined and 3D laser scanned welded replicas displayed in Figure 44 shows that the dimensional requirements were fulfilled.

Figure 43. Pre-machined and welded replicas

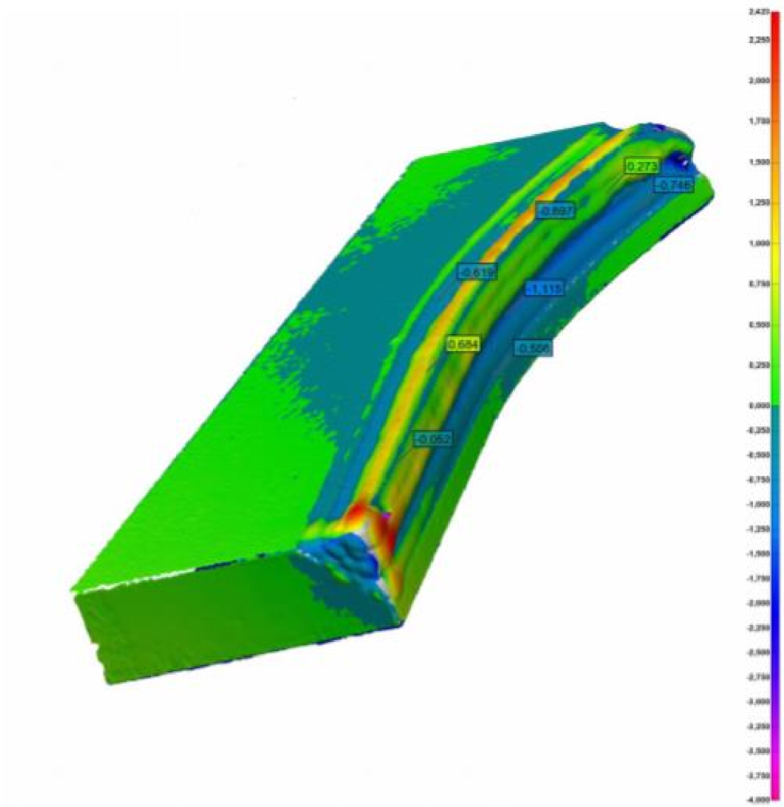


Figure 44. Buffer and hardfacing layers comparison to the sharp edge

The minus values mean that there is a slight shortage.

8. CONCLUSION

In this master's thesis, one filler metal and several hard-facing alloys were studied in order to repair the worn area of large industrial equipment by the CMT-WAAM method. To achieve this goal, these different materials were welded, characterized, and subjected to wear and tensile tests. The purpose of mechanical tests was to choose the best option for repairing the worn part studied.

Using the 3D laser scanner made it possible to digitize the part studied and to be able to restore, virtually, the worn area, becoming a very useful tool throughout the remanufacturing process. Once the material was chosen, a 3D laser scanner verified the correct dimensions of the welded part.

As it was observed in the wear tests, FeV12 can be considered as one of the potential candidates with good abrasion and wear resistance characteristics, but it is important to remark that the best hard-facings are "experimental" and NiFD PLUS samples, which outperformed the current case-hardened steel.

According to the tensile tests, the fusion line is not the weakest zone, so the adhesion is not an issue. The heat-affected zone is not the weakest zone either. It was found out that weld material is the weakest zone, which corresponds to the G69 class NiMoCr filler alloy. For this reason, higher strength welding wire should be selected.

Finally, after all the tests carried out and studying the results obtained, the worn part can be remanufactured and upgraded to a better condition than it was in the beginning.

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