UNIVERSIDADE FEDERAL DE SANTA CATARINA – UFSC

HOCHSCHULE NIEDERRHEIN - UNIVERSITY OF APPLIED SCIENCES

DURUM VERSCHLEISS-SCHUTZ GMBH

A NEW SOLUTION FOR WEAR AND CORROSION PROTECTION: ALTERNATING CURRENT MIG WELDING PROCESS WITH NICKEL, COBALT AND IRON BASIS FLUX-CORED HARDFACING WIRES

PEDRO CORREA JAEGER ROCHA

WILLICH, GERMANY

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Bachelor thesis presented to the Materials Engineering Course of the Universidade Federal de Santa Catarina to claim the title of Materials Engineer.

Supervisor: Herr Dr. Ing. Frank Schreiber

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This bachelor thesis was considered proper to the achievement of the title of Materials Engineer and approved in its final version by the Course of Materials Engineering of the Universidade Federal de Santa Catarina.

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To my friends.

Danke schön!

Abstract

Several relevant industrial areas of emerging countries' economic scenario, like oil extraction, agriculture and mining, rely on the *Hardfacing* process to reach their process efficiency. The *Hardfacing* technique consists on controlled deposition of materials with superior properties, like hardness, over parts made of inferior materials quality in these aspects. This deposited layer seeks an increase in corrosion and, specially, abrasive wear resistance of the component. In this work, three typical hardfacing flux-cored wires of Ni, Co and Fe basis were deposited by Flux-Cored Arc Welding (FCAW) in the special variant mode of Alternating Current (AC) using an OTC Welbee P400 power source. This non-usual welding mode, can be compared with other state of art "cold processes", like Fronius CMT and Lincoln STT, which are a tendency in the cladding area as an economical alternative to high-performance process like plasma transferred arc – powder (PTA-P), once it allows good deposition rates combined with low heat input, a vital aspect for cladding applications like *hardfacing*. This work aims not only the evaluation of the AC MIG efficacy in hardfacing applications, but, also to compare it with the other cold prosses like Fronius CMT. For the comparison, the flux-cored wire choose was the iron basis DURMAT FD 61, while the other wires were tested only with AC MIG. The results demonstrated high industrial success possibility in the hardfacing area. With outstanding results of deposition rates up to 8 kg/h with less than 10% of dilution, being as good as controlled short-circuit systems, and even better for higher deposition rates.

Keywords: GMAW, MIG/MAG, AC MIG/MAG, alternating current welding, hardfacing, *CMT, STT, cladding welding, flux-cored arc welding.*

Resumo

Várias áreas industriais de alta relevância no cenário econômico de países emergentes, como extração de petróleo e gás, agricultura e mineração, dependem de técnicas de revestimento duro por soldagem conhecido como *Hardfacing*. Essa técnica consiste no depósito controlado de materiais com propriedades superiores, como dureza, sobre peças feitas em materiais com qualidade inferior nesses aspectos. Essa camada depositada busca aumentar a resistência à corrosão e, especialmente, ao desgaste abrasivo. Nesse trabalho, três diferentes tipos de arames tubulares com base em Ni, Co e Fe foram depositados por Flux-Cored Arc Welding (FCAW) no modo especial de corrente alternada (AC) usando uma fonte de soldagem OTC Welbee P400. Esse modo não usual, junto a outros processos considerados “frios”, como o Fronius CMT e Lincoln STT, é uma tendência na área de revestimento metálico, uma vez que permite altas taxas de deposição combinadas a baixo calor aportado na peça, característica vital no *Hardfacing*.

Esse trabalho buscou não somente a avaliação da eficácia do processo citado na aplicação de *hardfacing* em chapas e tubos, mas também a comparação do processo em relação aos outros processos “frios”: Fronius CMT e Lincoln STT. Para a comparação, o arame tubular escolhido foi o DURMAT FD 61, enquanto os outros arames foram testados apenas com AC MIG. Os resultados demonstraram alta possibilidade de sucesso em aplicações industriais na área de *hardfacing*. Com resultados expressivos de taxa de deposição na faixa de 8 kg/h com menos de 10% de diluição, o processo demonstrou-se tão eficaz quanto os sistemas de curto circuito controlado e ainda superior para taxas de deposição mais altas.

Palavras chave: *GMAW, MIG/MAG, AC MIG/MAG, corrente alternada, AC, hardfacing, CMT, STT, cladding welding, flux-cored arc welding, revestimento duro.*

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1. Introduction

This work was done in a partnership between the company DURUM Verschleiß-Schutz GmbH, the Labsolda Institute of Welding and Mechatronics and the Hochschule Niederrhein University of Applied Sciences.

For one year, the author worked as a welding research intern at the DURUM Verschleiß-Schutz GmbH studying state of art welding processes and characterization methods in order to evaluate the reliability and feasibility of a new industrial solution for hardfacing.

1.1 Motivation

Most of the industrial research seeks for improvements in productivity and efficiency of a manufacture process. The first thing that comes in mind is a possibility to reduce prices with further comeback in market share gain or companies' profit increment. When we start thinking deeply in the production chain we can see further consequences like the appreciation of the natural resources consumed in the process. Its optimization leads to a smaller resources requirement to attend the same demand, meeting our needs without compromising the ability of future generations to meet their own needs. [1]

One case of optimization, per example, is the coating of hard materials over metallic parts surfaces, the so called *Hardfacing.* Some important industries such as agricultural, mining, chemical and oil extraction, take advantage of this technique with significant increase in parts lifespan. In other words, when covering some metal pieces with more "noble" materials they last longer. This happens basically due to the special properties of the deposited coat against deleterious conditions like corrosion and wear mechanisms.

The benefits that it brings to the whole production chain is clear when the hardfacing process optimization is made: less wasted resources in the hardfacing process itself and also high contribution to make the systems, where it is applied, more efficient too.

Each day it becomes more evident that as engineers we have the duty of build a more sustainable industry. Acting to optimize the existent processes and designing others less resource-consuming is one way to fight against our planet resources massive exploration. So, I assure that this mindset motivates the following objective.

1.2 Objective

Pursuing this work motivation, the following objective was projected and evaluated pertinent to the level of knowledge formation necessary to this kind of assignment.

- **To achieve high quality hardfacing deposits with DURMAT NIFD, DURMAT FD 61 and DUROLIT 6 flux-cored wires over conventional construction steel tubes. The Alternating-Current Flux-cored Arc Welding (AC-FCAW) process must be used. Factors like low deposit dilution (less than 10%), reliability and good deposition rates are requirements.**

- **After acquiring results for AC-MIG with DURMAT FD 61 the results must be compared with an earlier work about another cold process: Fronius Cold Metal Transfer (CMT).**

2. Literature Revision

To assist this work comprehension this chapter will introduce basic concepts of: Wear mechanisms, Hardfacing techniques, MIG/MAG and its specials modes, FCAW (Flux-Cored Arc Welding) process, Alternating Current welding process, Wear tests and some bases of the material studied in this work: DURMAT NIFD, DURMAT FD 61 and DUROLIT 6.

2.1 Wear

Wear has been recognized as meaning the phenomenon of material removal from a surface due to interaction with a mating surface. Almost all machines lose their durability and reliability due to wear, and the possibilities of new advanced machines sometimes are reduced because of wear problems. Therefore, wear control has become a strong need for the advanced and reliable technology of the future.

Wear rate changes drastically in the range of 10^{-15} to 10^{-1} mm^3/Nm, depending on operating conditions and material selections. These results mean that design of operating conditions and selection of materials are the keys to controlling wear. [2]

Koji Kato and Koshi Adachi define wear as the result of material removal by physical separation due to microfracture, by chemical dissolution, or by melting at the contact interface. Furthermore, there are several types of wear: adhesive, abrasive, fatigue, and corrosive. The dominant wear mode may change from one to another for reasons that include changes in surface material properties and dynamic surface responses caused by frictional heating, chemical film formation, and wear. In general, wear does not take place through a single wear mechanism, so understanding each wear mechanism in each mode of wear becomes important. [2] They also define the basic wear mechanisms as follows:

Adhesive wear and abrasive wear are wear modes generated under plastic contact. In the case of plastic contact between similar materials, the contact interface has adhesive bonding strength. When fracture is supposed to be essentially brought about as the result of strong adhesion at the contact interface, the resultant wear is called **adhesive wear**, without particularizing about the fracture mode. [2]

In the case of plastic contact between hard and sharp material and relatively soft material, the harder material penetrates to the softer one. When the fracture is supposed to be brought about in the manner of micro-cutting by the indented material, the resultant wear is called **abrasive wear**. [2]

In the case of contact in the running-in state, fatigue fracture is generated after repeated friction cycles. When surface failure is generated by fatigue, the resultant wear is called **fatigue wear**. In the case of contact in corrosive media, the tribo-chemical reaction at the contact interface is accelerated. When the tribo-chemical reaction in the corrosive media is supposed to be brought about by material removal, the resultant wear is called **corrosive wear**. In air, the most dominant corrosive medium is oxygen, and tribo-chemical wear of metals in air is generally called oxidative wear. [2]

The material removal in adhesive, abrasive, or fatigue wear is governed by deformation and fracture in the contact region, where fracture modes are fatigue, brittle, or ductile fracture. Such deformation and fracture are generated by mechanically induced strains and stresses. Therefore, this type of wear is described as **mechanical wear**. [2]

The material removal in corrosive wear is governed by the growth of chemical reaction film on wear surface, where chemical reactions are accelerated by frictional deformation, microfracture, and successive removal of reaction products. This type of wear is generally described as **chemical wear**. [2]

The macroscopic classifications in terms of mechanical and chemical wear are useful to a comprehensive understanding of wear once almost all models of wear are included in these three types. Four basic concepts of wear are summarized in the Figure 1 (*next page*). [2]

One way to increase the wear resistance of a metallic part is by coating with a more resistant material. Due to the different mechanisms of wear it is necessary to have different approaches to fight against each mode. The company DURUM, per example, produces very specific alloys and process for each kind of wear situation which the part welded will be exposed to. The next topic will explain some welding basic and welding hardfacing technics used to prevent abrasive wear inconvenient effects.

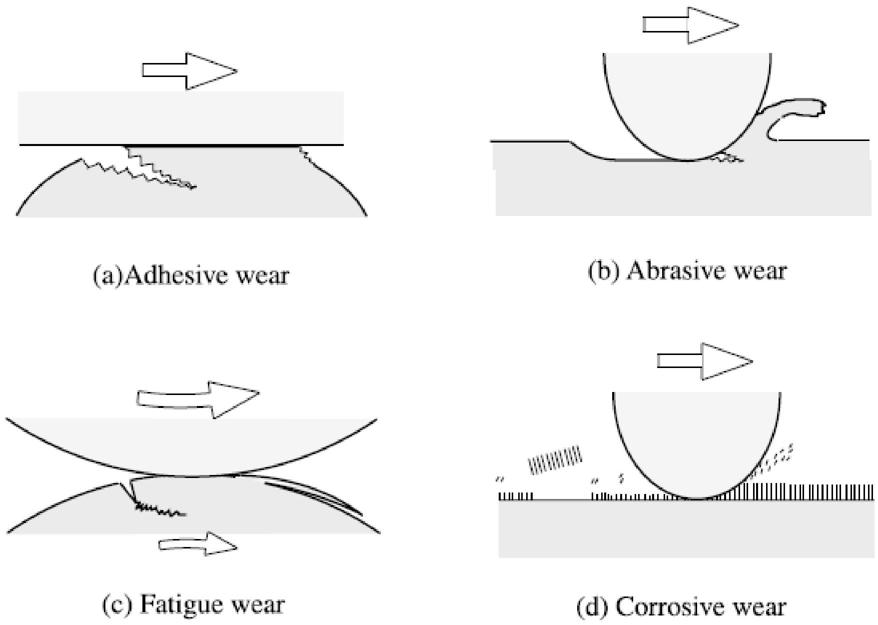


Figure 1:Schmatic figures of four representative wear modes. [2]

2.2 Hardfacing

Hardfacing can be defined as the deposition of a special alloy on a metallic part to obtain more desirable properties than the previous surface. Usually seeks for a harder surface, where the name comes from. This technique is used to provide greater resistance to wear from abrasion, impact, adhesion, heat, corrosion or any combination of these factors. A wide range of hardfacing alloys are available for practically any part. Some alloys are very hard, other alloys are softer, but with hard abrasion resistant particles dispersed in its matrix, like one of the materials studied in this case: DURMAT NIFD. Certain alloys are made to rebuild a part to a required dimension while others are designed to be a final overlay that protects the work surface. [3] The main hardfacing alloys can be split in three categories: iron basis, nickel basis and cobalt basis. These alloys are usually combined with ceramics hard particles forming composites also known as pseudo-alloys or "cermet". These hard phases can either be nucleated during the process due to special alloys elements like Vanadium or be added, per example, as powder, and keep its solid state during the process resulting in an embedded hard particle after the lower melting point matrix solidification.

Even though the name *Hardfacing* comes due to the increased hardness particles formed or embedded in the deposited alloy, Coronado shows in his study, the relationship of hard particles and soft, but tough, matrix is much more important than the hardness of the particles itself. [4]

Chotěborský stands that hardfacing is a commonly employed method for agricultural tools, component for mining operation, soil preparation equipment, oil and gas extraction and other industries. [5] So the base industries of raw materials and commodities are closely related to wear issues. These industries have great impact in emerging countries' economy, like Brazil, reaffirming the importance of this work.

Some benefits of hardfacing are the cost reduction due to reconditioning of a worn part instead of a replacement to a new one, with saves from 20 to 70%. Equipment lifespan prolongation up to 10 times are common with a properly overlay. This leads to minimization in service downtime since fewer shutdowns are required. Also, less spare parts in the inventory are required once worn parts can be rebuilt. [3]

Hardfacing can be applied by a number of welding processes. Selection of the most suitable welding process for a given job will depend on a number of factors like: nature of work to be hardfaced, function of the component, base metal composition, size and shape of component, accessibility of weld equipment, state of repair of worn components, number of same or similar items to be hard-faced etc. There are various processes for *hardfacing*, the most known ones are: Shielded Metal Arc Welding (SMAW), Flux Cored Arc Welding (FCAW), Oxy-Fuel Gas Welding (OFW) and Plasma Transferred Arc Welding (PTA). Other processes are used as well but in minor scale. [6]

Like states in this work's objective, the hardfacing process employed was the flux-cored arc welding with an Alternating Current electric mode. The next subchapters will explain both concepts.

2.3 MIG / MAG welding process

This welding process is known as MIG/MAG (metal inert/active gas). Its main characteristic is the continuous and mechanized metal addition in form of wire. On the final extremity of the wire an electric arc is generated with sufficient energy to controlled melt the wire, that is feed in a rate fast enough to deposit the material without extinguishing the arc, like Figure 2 shows. [7]

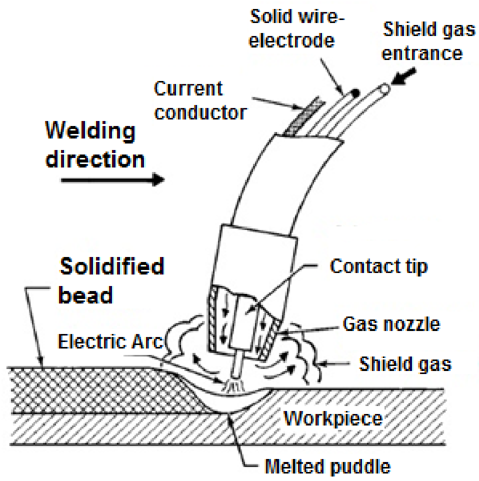


Figure 2: Schematic graphic of MIG/MAG torch during the welding process.

The electric arc is generated due to the ionization of the gas, that is uninterruptedly feed around the wire like Figure 2 shows. This gas is called “Shielding gas” since it serves not only as medium for the electric current flow but also protect both the metal droplets that come from the melting wire and the molten puddle that lies over the ground material. When this gas is inert (*Argon*, e.g.) the process is called MIG, on the other hand when the gas is active or a mixture of active and inert gases ($Argon+O_2$, e.g.) the process is called MAG. Another common denomination for this process is GMAW: Gas Metal Arc Welding, [8]

A motor pushes the coiled wire through a liner until the end of the welding torch. There is a difference in electric potential energy between the wire and the metal workpiece. This artificial tension is generated by the welding power source, in which the electric welding parameters, like electric current or electric tension, can be choose. With the wire (anode) progress in direction of the workpiece (cathode) the electric field between both electrodes rises. The attraction of the electrons on the tip of the wire, due to the electric tension imposed by the welding power source, rises to the point that the shielding gas dielectric strength between the electrodes is broken. When this happens, the gas turns to an electric conductor. So, the shielding gas is also known as the ionizing gas. The dielectric strength break is seen with the aperture of an electric arc, which can be understand as a series of electric discharges between cathode and anode (wire and workpiece).

The electric current through the electric arc, in this process, usually ranges from values of 40 to 400 A, with electric tension about 20 V, generating the heat that will melt the wire and the ground material. Normally this current flow has only one direction during the whole process and it is called DC (*direct current*) process. The current flow can be straight (electrode-negative) or reverse (electrode-positive). Each current flow direction gives the process different pros and cons. A process where the polarity alternates between straight and reverse is called AC (alternating polarity), it will be better explained in the next subchapters.

2.4 Advanced MIG/MAG processes

During the time, new complex welding tasks, came out from many engineering areas. This constant challenge allied with the development of new electronic technologies, that allowed the welding power sources to be more intelligent and stable, resulted in advanced MIG/MAG processes. Hardfacing applications are benefited from relatively new advanced process called “cold” processes. These processes are variations that allow same bonding quality with far less energy, crucial to hardfacing solutions. The first advance was pulsing the electric wave to determine when and how the metal transfer would occur, latter more control was able with processes like Fronius Cold Metal Transfer and others.

2.4.1 MIG/MAG pulse

Pulsed MIG/MAG is a modified process in which the power source switches between a high peak current or voltage and a low background current or voltage between 30 to 400 times per second. During this switch, the peak current pinches off a droplet of wire and propels it to the weld joint. At the same time, the background current maintains the arc but produces such a low heat input that metal transfer can’t occur, allowing the weld puddle to solidify. [9]

This action differs from a traditional spray transfer process, which continuously transfers tiny droplets of molten metal into the weld joint. There are two different types of pulsed GMAW processes: synergic and non-synergic. In a synergic pulsed MIG/MAG system, the power level automatically adjusts to the wire speed as it changes. This is the most common method in welding equipment today, as it is the easiest for welding operators to set and achieve good welding parameters. Some advantages are: less spatter, higher deposition rates, deeper penetration. [9]

2.4.2 Cold metal transfer (CMT)

The cold metal transfer (CMT) welding process was patented by FRONIUS in 2004 and is based on a dip metal transfer mode. The system is equipped with a high-speed digital control, inverters and a processor that control all the process, for instance, the length of the arc, the current and the voltage. Whereas the material transfer in dip transfer welding is controlled electrically, the CMT process controls material transfer via both the initiation and duration of the short circuit and mechanically assisted methods. The main innovation is the reverse of the wire by a specialized servomotor incorporated into the gun that can oscillate the wire at the moment of the short circuit occurrence to assist with droplet detachment. The metal can then be transferred to the molten pool with the retraction force and the electromagnetic force of the welding pool. Figure 3 shows the current and voltage waveform of the CMT process and the principle of the droplet and electrode motion sequence. The droplet detachment occurs at almost zero current input. [10]

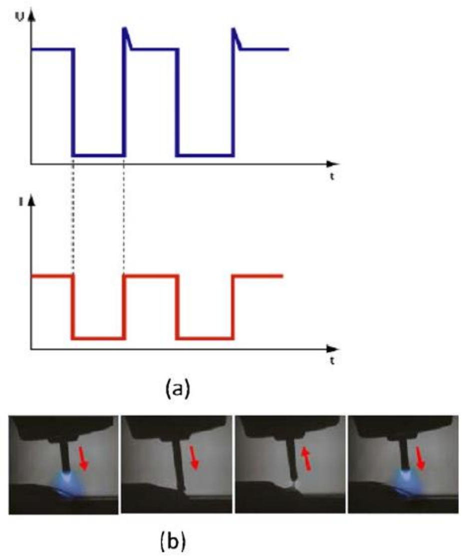


Figure 3: (a) CMT tension (U) and current (I) curve. (b) droplet and wire electrode motion sequence. [10]

2.4.3 Alternating Current (AC)

Alternating current in welding processes is not the most usual mode. In the industrial welding operations, the electrical current commonly flows only in one direction instead of alternating. [11]. In this fashion, there is a transition from positive current values to negative without interrupting the arc as Figure 4 shows.

The objective is basically to decrease the heat input over the work piece. In a recent work, Dutra et al characterized this mode as a “cold process” together with processes like Fronius CMT, already mentioned in this work. [11] Good results welding thin plates brought attention to the mode despite of it irregular arc stability. [10] Other valuable result of low heat input benefits overlay processes like cladding and hardfacing: the low heat input help keeping low dilution between base and additional material, at the same time maintaining the productivity. [12]

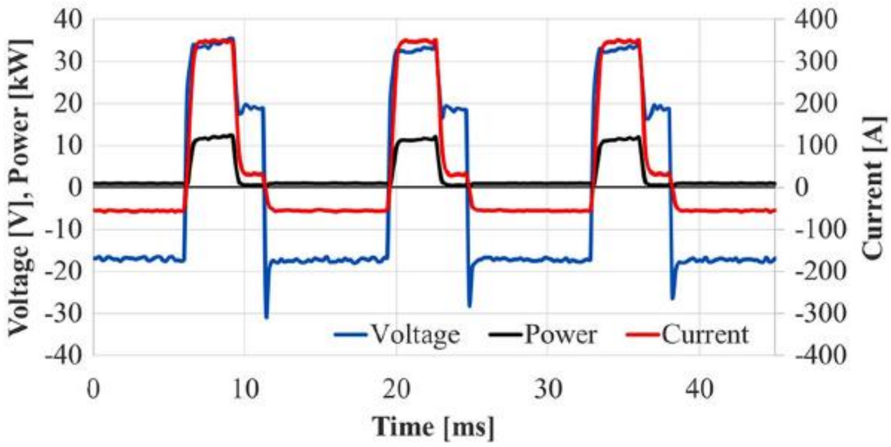


Figure 4: Pulsed AC electric wave graphic. The current alternate between positive and negative. [11]

Talkington stands that when using the positive polarity in MIG/MAG with a gas mixture of Argon and less than 5% of O_2 or CO_2, around 30% of the arc heat keeps in the wire electrode and 70% of the heat flows to the work piece. With negative polarity, only 30% of the arc heat flows to the work piece. [13] When the wire is the cathode (negative polarity) the arc rises seeking the conditions most favorable to field electron emission. [11] [14]. The arc climb is a response of the cathodes spots’ electron emissions located in the oxides up in the wire. When the polarity is positive the cathode spots are over the work piece. [11] With a more spread arc the pressure over the work piece decreases and at the same time more wire can be fused once the arc is higher. This leads to less penetration and less dilution. [11] The difference can be seen in the figures 5 and 6.

Although the heat input is one of the factors that contribute to low dilution levels, Dutra et al point out that the metal transfer type still acts as the main controller of the dilution. [11] Talkington stands that the transfer mode in AC is limited to the globular transfer [13]. In other hand, Souza et al [15] showed that depending of the welding gas it is possible to set regular free-flight non-repulsive droplet transfer with alternating polarity. Dutra et al also achieved a sound ODPP (one drop per pulse) transfer parameter after developing an AC parameterization methodology that focus in setting equal wire fusion rates for EN, electrode negative, and EP, electrode positive [11].

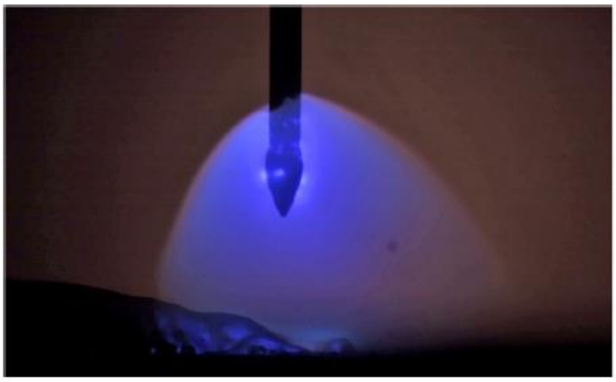


Figure 5: Negative Polarity. The arc climbs up the wire. Cathode spots visible on the wire. [11]

Figure 6: Positive Polarity. The arc anchors at the end of the droplet. [11]

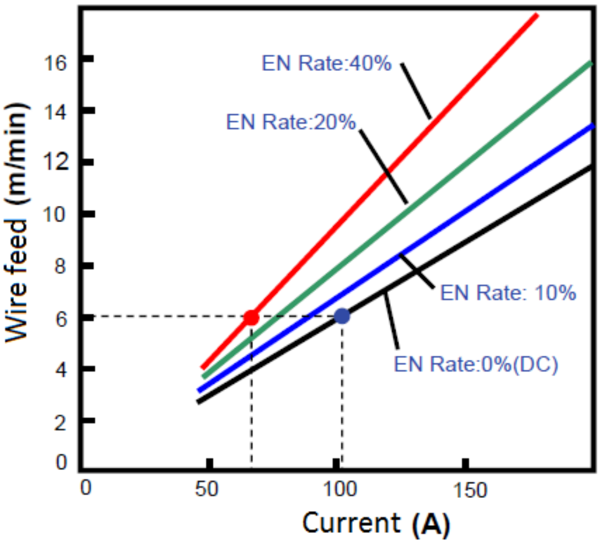


Figure 7: Chart of fusion rate of wire A5356 1,2mm with four EN rates. [28]

The Figure 7 presented by OTC Daihen shows a comparative graphic of fusion rate with different EN rate. Where EN rate is defined with Equation 1 where "I" means the electric current intensity mean value in positive and negative.

$$EN\ ratio\ \frac{I_{EN}}{I_{EP}+I_{EN}}\ X\ 100\% \qquad (1)$$

2.4.4 Flux cored arc welding

Flux cored arc welding (FCAW) uses the same type of power sources, wire feeders, and welding guns as MIG/MAG. However, flux cored arc welding incorporates the use of a tubular electrode with a core containing flux. A variation, self-shielded flux cored arc welding, also called "open arc", obtains its shielding gases from the electrode and requires no externally added gas. Figure8 illustrates both gas shielded and self-shielded flux cored arc welding. [16]

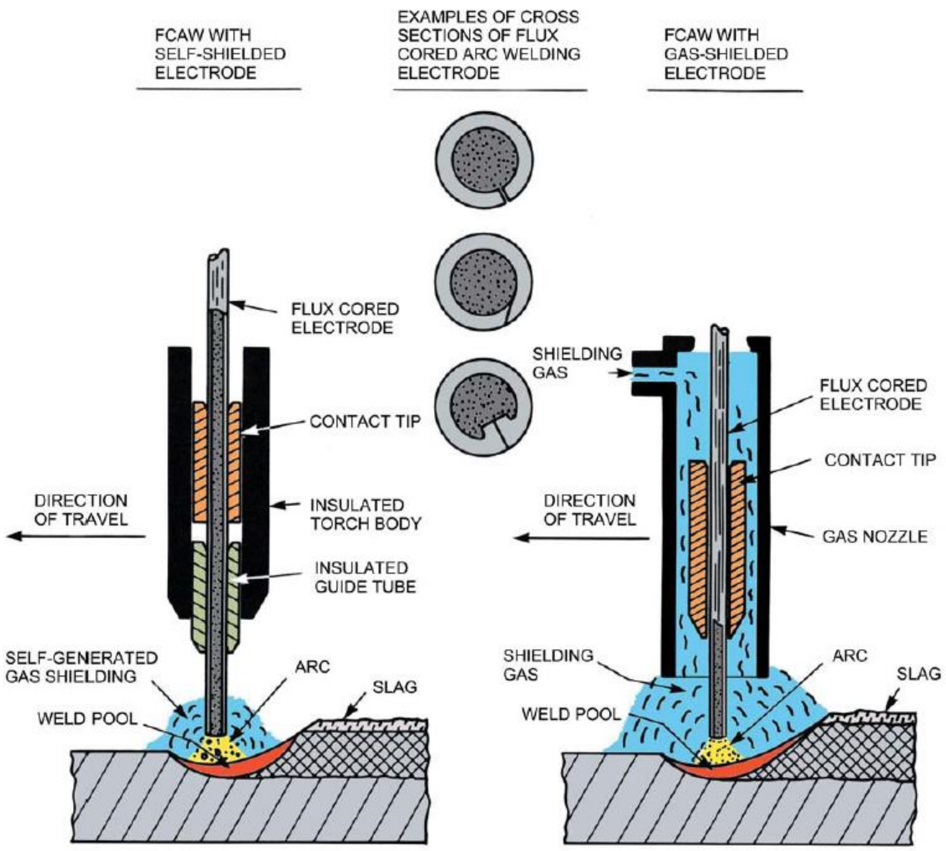


Figure 8: Schematic representation of flux cored arc welding. [27]

The flux in the electrode core stabilizes the arc and contains deoxidizers, scavengers, slag, and vapor-forming ingredients as well as hard particles (carbides) for hardfacing applications. [16] Consumable electrodes can be find in a range of compositions: carbon steel, nickel basis, cobalt basis among others alloy. Electrode sizes range from less than 0.5 mm to 4 mm. Deposition rates in FCAW are higher than those attained with conventional MIG/MAG. The presence of flux as part of the process enables beneficial chemical reactions as does the coating ingredients on the SMAW electrode. However, the productivity potential is significantly higher than with SMAW due to the high current density used with this process and the fact that it is not necessary to stop to change electrodes so often. [16]

2.5 Wear resistance tests

As important as the hardfacing process is the properties analysis. Even though corrosion and other failures also are benefited by hardfacing, in this work only the wear resistance analysis will be present. Two approaches were taken to confirm the wear protection efficacy and compare the different materials between each other.

2.5.1 ASTM G65 – Rubber-Wheel test

The resistance to scratching abrasion by means of a dry sand flow between a metallic sample surface and a rubber wheel, like the Figure 9, can be measured by the ASTM G65 test. [17]

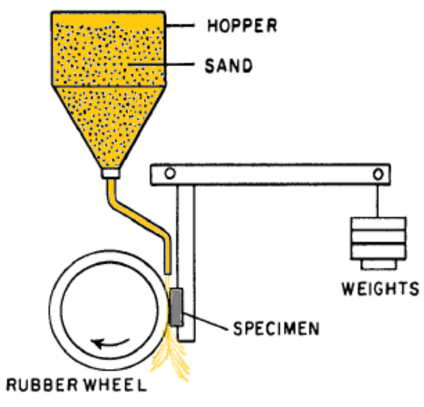


Figure 9: Schematic Diagram of ASTM G65 Test Apparatus. [17]

The apparatus shows a lever linked with a standard weight that press the sample surface against a rubber wheel with a specified force while the wheel rotates in a controlled speed. The sand flow starts to wear the specimen, that is weighed before and after the test and the loss in mass recorded. It is necessary to convert the mass loss to volume loss in cubic millimeters, due to the wide differences in the density of materials. [17]

The test parameters can be modified according to the properties of the specimen. More wear resistant materials need more aggressive parameters. The parameters differ in time and force applied, from "*test modification*" "A" to "E", where "A" is the more aggressive and "E" the less aggressive. [17]

Once you can choose the abrasive media, the test severity depends upon the abrasive particle size, shape, composition etc. Standard sand is required for comparison of abrasion resistance of different materials. It is important to state that this test gives only a prediction of which material will probably be more effective, so an abrasive resistance material rank can be made. For more detailed information the fully standard reference must be consulted as follows in bibliography item [17].

2.5.2 ASTM G75 – Miller test

The Miller Number test has been around since 1967, and it was originally developed to determine the abrasivity of slurries. Since then it has evolved into a test to measure the relative abrasivity of many slurries and has been adopted by the ASTM as G75-2001: "Standard Test Method of Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (SAR Number)." Specific definitions of those two numbers are given in the Standard and are quoted here [18]:

"**Miller Number**– a measure of slurry abrasivity as related to the instantaneous rate of mass loss of a standard metal wear block at a specific time on the cumulative abrasion-corrosion time curve."

"**SAR Number** – a measure of the relative abrasion response of any material in any slurry, as related to the instantaneous rate of mass loss of a specimen at a specific time on the cumulative abrasion-corrosion time curve…"

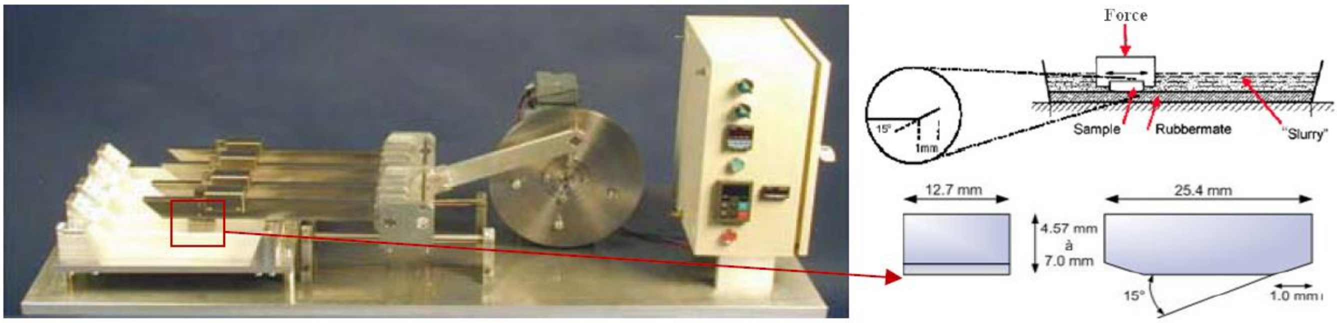


Figure 10: Picture of Test Apparatus and Specimen dimensions. [26]

"The drive mechanism provides a horizontal motion to the specimen arm of 200 mm travel. The arm is freely pivoted to a crosshead at a point that results in the arm being parallel to the crosshead ways in the operating position. The crosshead is connected to a crank, rotating at 48 r/min, by an appropriated connecting rod" [19]. The Figure 10 shows the test apparatus and the standard specimen dimensions.

The apparatus used in this test had 4 arms to make 2 duplicated tests simultaneously. Each arm is loaded with a mass so that the total downward force on the face of the wear block is 22.24 N (5 lb.). Troughs with about 50 mm x 381mm by 50 mm high are used. [19]

For each test, the bottom of the trough is equipped with a neoprene lap. The interior of the trough has a flat-bottomed shape trough that confines the slurry particles to the path taken by the specimen. At one end of each stroke, the specimen is lifted off the lap by a cam action for sufficient time to allow fresh slurry material to flow under the wear block. The test consists of 3 increments of 2 hours, a total of 6 hours test. At each 2 hours round the specimen is cleaned and weighted. [19]

The abrasivity is determined by the measured mass loss of the specimen. The higher the SAR number is, less resistant to abrasion is the hard-faced deposit. [19]. To calculate the SAR number its necessary first to discover the coefficients A and B of the designed curve fit equation 2.

$$M = At^{B} \quad \textbf{(2)}$$

Where "**M"** is the cumulative mass loss [mg], "**A"** is the first curve fit coefficient, "**B**" is the second curve fit coefficient and "**t"** is the time [h]. Any acceptable curve fit method may be used to compute the values of A and B.

The Miller Number and the SAR number are described as indexes related to the rate at which the wear block or specimen loses mass at 2 h into the test, which can be calculated by using the first derivative of Equation 2 at 2 h and is designated as **dM**. This become the slope of the line tangent to the curve at 2 h as seen in Equation 3.

$$dM = ABt^{(B-1)} \quad \textbf{(3)}$$

It is desirable to have a meaningful whole number for the expression. So there is a scaling factor (**C**), determined to be 18.18 [h/mg] that is multiplied for **dM** to result in the Miller Number **MN**. The result must be rounded to the nearest integer.

$$MN = dMC = 18.18 * dM \quad \textbf{(4)}$$

Now to calculate the SAR number the last step is to multiply the Miller number **MN** by the ratio of the standard wear block material specific gravity, used to determine slurry abrasivity, (7.58) to the specific gravity of the specimen (SGS).

$$SAR = MN * \frac{7.58}{SGS} \quad \textbf{(5)}$$

Once any slurry/specimen couple relation can be measured with this test, it turns to be the best way to fit materials for abrasive real conditions, but also to rank wear resistance between different materials, like was made in this work.

2.6 DURMAT NIFD

DURMAT NIFD is a hardfacing flux cored wire developed by DURUM Verschleiß-Schutz. It consists in a nickel basis flux-cored wire filled with *Fused Tungsten Carbide* (FTC) hard particles. NIFD was developed to protect surfaces against extreme abrasive wear in combination with corrosion attacks. The deposits, as can be seen in page 38 , consists of approximately 50-65% FTC and 35-50% Ni-Cr-B-Si- matrix. [20]

The alloy has a low melting range between 900-1050 °C and features a self-fluxing characteristic producing a smooth and clean surface. The matrix is highly resistant to acids, bases, lye and other corrosive media.

The Figure Figure 2121 shows a zoom of Figure 20 revealing the carbide dispersion through the matrix. The micro hardness profile points are marked in red triangles. The carbides show a hardness average of 2346 $HV_{0.5}$ and the matrix 540 $HV_{0.5}$. [20]

DURMAT NIFD main application is in the repairing and hardfacing of ferritic and austenitic steel tools and machine parts. Specially for tool joints and stabilizers in the petroleum industry. Due to its hard carbide particles, this coating is more efficient in areas of large particle abrasion and moderate impact. [20]

It can be seen, in Figure 22 and Figure 23 the microstructure of the hardfacing deposit.

The most important component of this cermet composite, or pseudo alloy, is the DURMAT FTC, or *fused tungsten carbide*. FTC is the eutectic composition of WC and W_2C. The average carbon content is between 3.8 and 4.1 wt. % and the phases can be estimated to be approximately 78-80% W_2C and 20-22% WC. [21]

FTC abrasion resistance is superior in terms of wear resistance to all other commercially available materials except diamond. It is far superior to any of the chromium carbide. The “feather” structure formed due to a special rapid cooling process gives this carbide its special properties. [21]

The deposition rates and material loss calculated in this work are based in the weight per length of wire: **17.85** g/m.

2.7 DUROLIT 6

DUROLIT 6 is the most commonly used cobalt-based flux-cored wire for FCAW applications. DUROLIT 6 deposits a cobalt-based alloy with an austenitic structure. This structure exhibits dispersed hard chromium and tungsten carbides within the CoCr-matrix. The DUROLIT 6 alloy offers excellent resistance of chemical and mechanical degradation such as, corrosion, impact, self-mated anti-galling, cavitation-erosion, wear at high temperatures and thermal shock. [22]

With an elevated service temperature, up to 750°C, some common applications are valves, seats, tong bits, shear blades, bearing areas, bushings (rollers), extrusion screw flights, pumps for high temperature liquids.

The deposition rates and material loss calculated in this work are based in the weight per length of wire: **13.75** g/m.

2.8 DURMAT FD 61

DURMAT FD 61 is a flux cored wire for hardfacing and is resistant to extreme abrasive wear. The deposit has a ledeburitic structure with a high content of different hard phases. DURMAT FD 61 is used at extreme abrasive wear due to its excellent resistance against abrasion. The deposit is free of slag, weldability is excellent. The deposit is free of slag, weldability is excellent. [20]

The deposition rates and material loss calculated in this work are based in the weight per length of wire: **11.3** g/m.

3. Equipment, materials and methods

3.1 Equipment

In this work, an OTC Welbee 400P power source was used. Metal plates were clamped on a welding table and pipes on a turn table and then the *hardfacing* process was executed by means of a CNC unit.

The hardness measurements were made with a *Ahotec* Vickers tester. A *Zeiss AXIO* observer light microscopy, automatic grinder/polisher was used for metallography purpose.

For the abrasion tests, special machines following strictly ASTM G75 and ASTM G65 requirements were used. A very import equipment was the *Kern ABJ-NM* high precision balance with 0.001 grams sensitivity, critical to the abrasion test reliability.

3.2 Materials

To ensure the comparison of the experiments the substrate is consistently the same common S235 construction steel plates and pipes, Table 1 brings the chemical composition. The protective gas chosen was 100% welding Argon, conferring the process the nomenclature MIG, *metal inert gas.*

The Table shows the flux-cored wires previous presented chemical compositions by weight percentage.

Table 1: Chemical composition range of the hardfacing flux-cored wires.

Wire	Chemical composition [weight %]									
	Ni	**Fe**	**Co**	**C**	**Cr**	**W**	**B**	**Si**	**Mn**	**Nb**
DURMAT NIFD	**Bal.**	0.2	-	2.4	-	49.8	1.3	0.01	-	-
DURMAT FD 61	-	**Bal.**	-	5.2	22	-	1	1.3	0.4	7
DUROLIT 6	-	2	**Bal.**	1.1	27	4.5	-	1	0.6	-

Table 2: Chemical composition of ground material.

Plate	Chemical composition [weight %]			
	C	Mn	P	S
S235	0.22 max	1.60 max	0.05 max	0.05 max

3.3 Methods

The first precaution to acquire reliable welding parameters data was to guarantee the steel plates' surface quality by controlled grinding. The surface must be free of rust or any discontinuity that may interfere in the electric current, ruining the arc stability. Nonmetallic dirty can also decompose with the heat and the gas flow may cause defects like porosity and lack of fusion of the substrate, leading to an unhealthy metallurgical link between hard coat and metal base.

To find the first welding parameters, linear single beads were made in plates of 100mm x 150mm x 25mm. After finding beads with good exterior aspect, like bead concavity and low spatter, a cross section was cut to have a first notion of the dilution.

Once reliable results of single beads are reached, weaving beads were made on plates with the same methodology of the single string beads. After that a hardfaced area was proposed with three overlaid weaving beads and later a structural steel 7 inches (177.8 mm) outer diameter pipe was also hardfaced to simulate an industrial application.

With a sound hardfaced plate, a cross section was cut by diamond disk cut-off machine to make the macroscopy and microscopy images that will serve to evaluate the dilution, microstructure, hardness profile as well as carbide distribution and wear tests.

The plates were weighted before and after welding. The open arc time measured, then, the deposition rate calculated.

One of the most significant results pursued is the abrasion resistance of the weldment. The following subchapters explains the testing methods. For the wear tests, samples of the hardfaced results were cut in the standard specified dimension and the surface made even to test after process wear resistance.

3.3.1 Dilution Measurement

The areas method was used to measure the dilution of hardfacing material with ground material. Basically, a base line is defined according to the ground material edge and both added material areas above and below the line measured. The equation 6, based on Figure 11, shows the method and the practical example. The bead resulted in a 5,46% dilution.

Cladding applications, like hardfacing, always seeks low dilution level, but keeping a sound metallic bonding between both ground material and overlay.

The software utilized to make the area measurements is the open source Fiji, the area results seen are measured in pixels. [23]

$$Dilution = \frac{A_2}{A_2+A_1} = \frac{7609}{7609+131306} = 5{,}46\ \% \qquad \textbf{(6)}$$

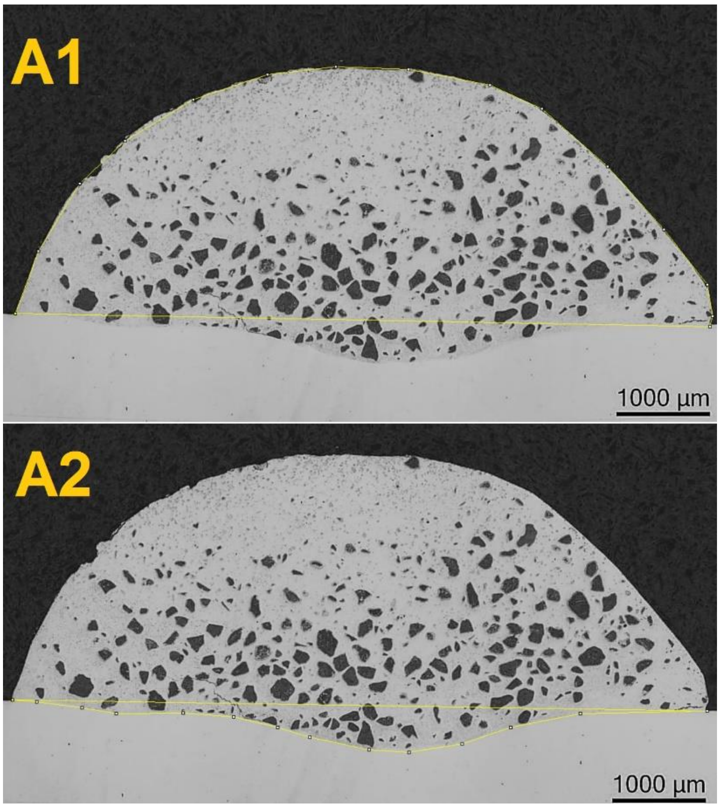


Figure 11: The yellow line defines the areas that are calculated by the Fiji software, showing the area measurement method.

4. Results

This chapter brings the AC MIG tests results, comparisons of DURMAT FD 61 hardfacing with CMT and AC MIG process and some brief comments of this work development.

4.1 AC MIG welding parameters study

The AC-MIG process, as explained in page 19, has special parameters choices like EN ratio and Electric Arc Characteristic. To evaluate these choices and understand how they affect in the results for the three wires, comparative tests were made. The next subchapters will bring the concepts of each parameter.

The first presetting, used in all the tests for this work, was the 1,6 mm Aluminum wire synergic program. It was chosen between the available choices that the OTC power source presents once it appeared to be the program that cares the most with saving heat input, meeting the requirement of low heat input of hardfacing technics. After programed attempts, the indicated electric parameters were slightly modified until a sound bead with good arc stability was find. The most stable pre-parameters are listed on Table 3. They give the initial parameters for stringer beads. Chart 1 shows an example of the AC wave for DURMAT NIFD, the welding current on Table 3 represent the welding current during the process.

Table 3: Stringer beads presetting parameters. *Forehand.

WIRE	Welding speed [cm/min]	Wire feed rate [cm/min]	Torch angle* [°]	EN ratio [-50/50]	Welding Curent [A]	Welding Voltage (V)	Arc Charact. [-10/10]	Arc adjustment [-100/100]	Gas flow [l/min]
DURMAT NIFD	40	450	15	50	190	17.2	0	10	15
DURMAT FD 61	45	450	0	50	180	17.5	0	10	-
DUROLIT 6	65	550	15	50	240	16	10	10	15

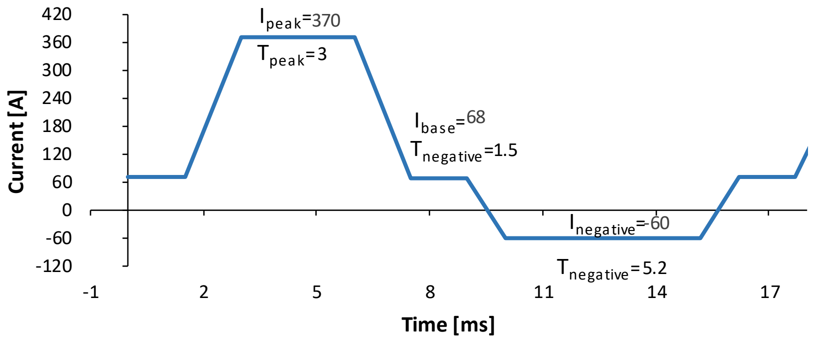


Chart 1: Electric wave pattern for AC-MIG presetting example for DURMAT NIFD.

4.1.1 Travel angle

During the tests, slight modifications in the travel angle showed relatively great difference in the results. It was expected to have better results with a pushing travel angle (forehand technique), once it is known to result in less penetration, wider and flatter bead. [9]

The fact that the arc is directed ahead of the weld puddle decrease the arc pressure over it, thus, results in less penetration of the ground material. In this parameterization, the “coldest” parameters were aimed, not only because of dilution, but, for FTC (fused tungsten carbide) conservation in case of DURMAT NIFD welding. An angle of 15° was used. Figure 12 may help the understanding.

Figure 13, 14 and 15 bring some visible differences. The most important aspect to note is the height, width and specially the FTC distribution on the top of the beads. The pictures are from DURMAT NIFD stringer single beads since the travel angle is especially important for this wire.

Bead 3 is wide and has small height. Can be considered as flat. The most important: FTC spread over the top. Bead 4 was welded dragging, backhand technique. It shows another profile. With smaller width, but higher height. Once it is taller than Bead 3, it’s top is near to the torch, and consequently in a hotter arc area. There is a lack of carbides on the top of Bead 4. Bead 5 was welded in the conventional way: torch perpendicular to the workpiece. Shows less lack of carbides on top comparing to Bead 4, but still some.

Both dilutions are low and below the 10% maximum required as shows Table 4Table.

Other beads with different parameters were tested and the 15° pushing travel direction method showed better carbide distribution in all cases.

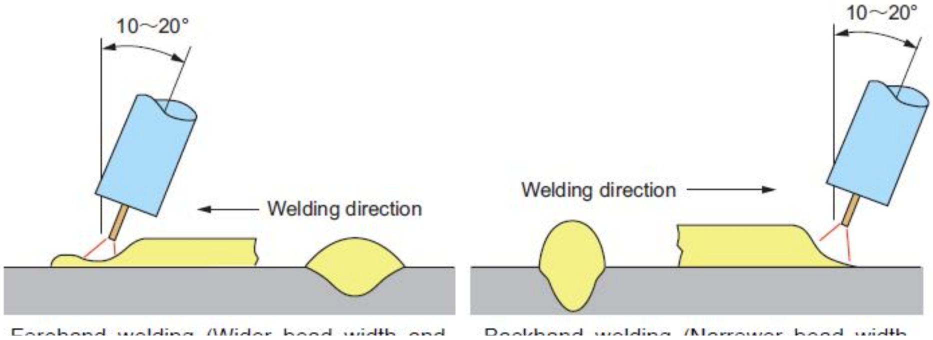


Figure 12: Schematic representation of travel angles generalized effect on the bead. [29]

Table 4: Bead measurements comparison.

Bead	Dilution [%]	Height [mm]	Width [mm]
3	3.5	2.2	8.2
4	2.1	2.7	6.3
5	3.2	2.5	7.9

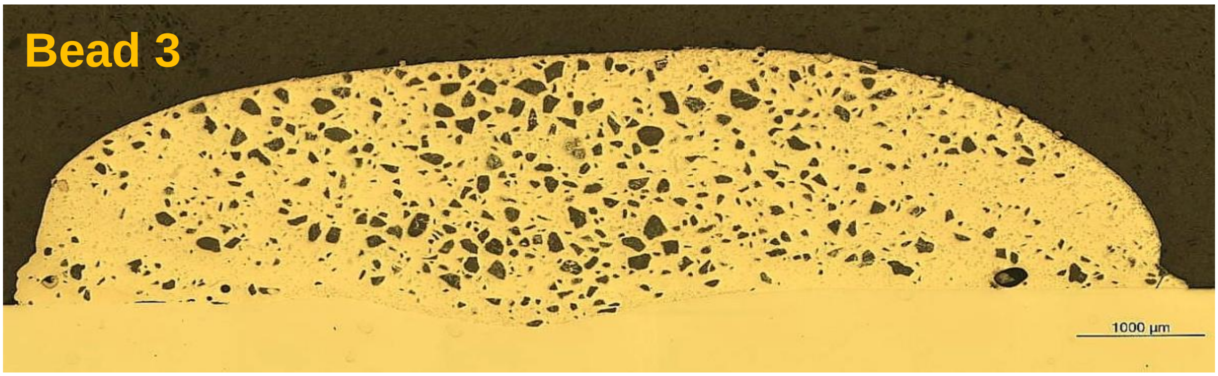


Figure 13: Forehand welded bead macrograph. FTC is spread on the top. Etched with Murakami.

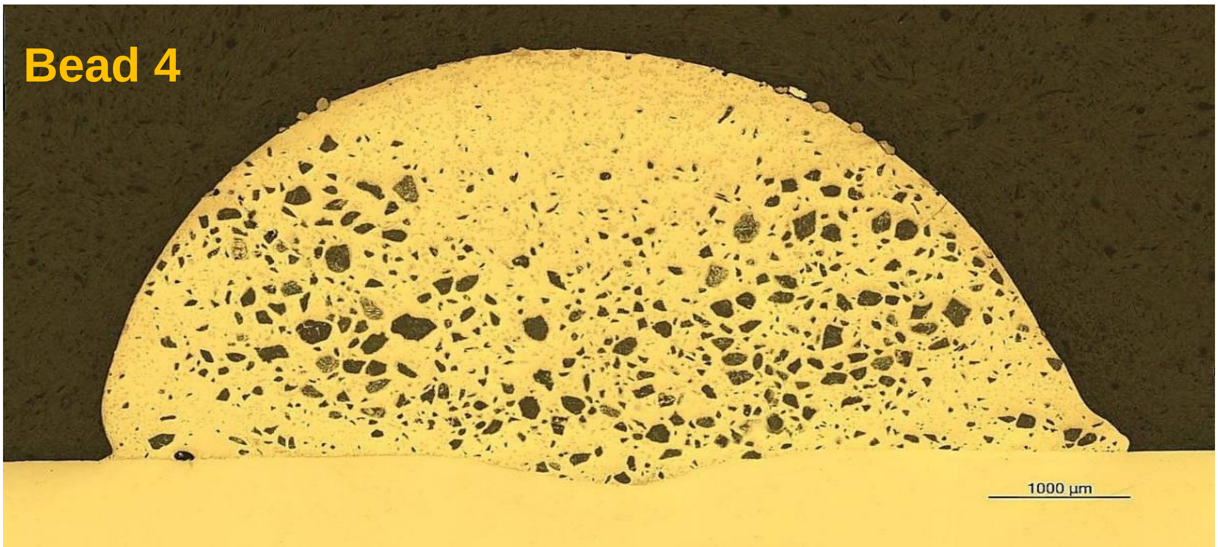


Figure 14: Backhand welded bead. Lack of FTC on top. Etched with Murakami.

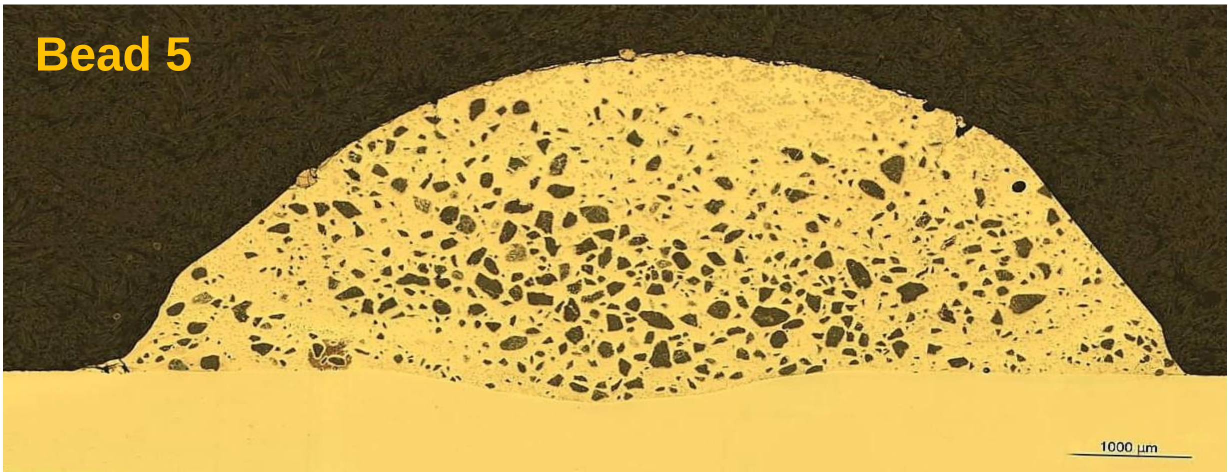


Figure 15: Torch perpendicular to the workpiece. Etched with Murakami.

4.1.2 Arc characteristic

This parameter ranges from **-10** to **+10**. It determines the arc stiffness or rigidity. From soft to hard. A positive arc characteristic is expected to spread more the arc, making its shape more like a Mexican hut than the famous bell shape. On the other hand, the negative arc characteristic claims a harder arc looking like a needle. In this test, the key welding parameters used for both beads are presented in Table 5Table .

Table 5: General parameters for this test.

Welding speed [cm/min]	Wire speed [cm/min]	Torch angle [°]	EN ratio [-30/30]	Welding Curent [A]
60	700	15 (forehand)	30	167

Seeking to spread more the energy, and, thus, reduce the heat input, an arc characteristic of **+10** was proposed for comparison. Figure 16 brings the macrography of both beads and Table 7 some interesting results.

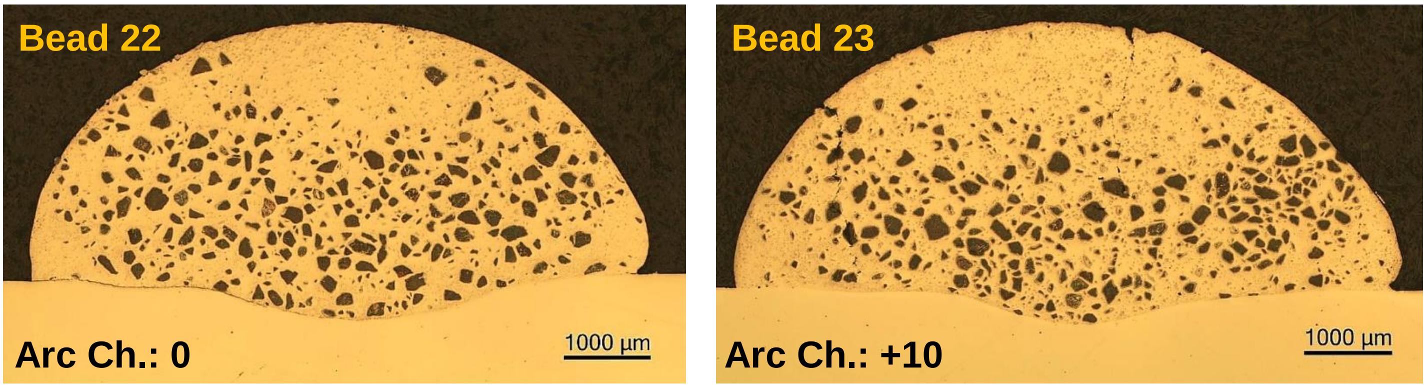


Figure 16: Comparison between beads 22 and 23 due to arc characteristic parameter rise. Etched with Murakami.

Even though the same energy amount was input, a more spread arc resulted in less dilution. However, in this low level of dilution (less than 10%) the measurement error must be considered high. Another factor is that the arc instability increases when using softer arc shapes.

Table 6: Results comparison between beads 22 and 23.

Bead	Arc Charact. [-10/10]	Dilution [%]	Bead height [mm]
22	0	7.67%	3.1
23	10	4.62%	3

This behavior is equally seen for both three wires, otherwise, this parameter adjustment it was more helpful with DURMAT NIFD since the energy input relationship between having a good metallurgical bond and at the same time maintaining the FTC on the top is very sensible.

4.1.3 EN ratio

The EN ratio parameter means the period ratio in which the base metal is positive and the torch is negative. The parameter ranges from -50% (what would be DC with the wire postive) and +50% (the general maximal EN ratio with good arc stability.).

The expected results increasing EN ratio are: higher deposition rate, less penetration (due to the reduced heat input) and taller beads. Tests were made to evaluate the EN rate variation effect in dilution, FTC distribution, bead shape, material loss, etc. The parameters and results are presented in Table 7 for NIFD.

Table 7: EN rate results comparison.

Bead	Welding speed [cm/min]	Wire speed [cm/min]	EN ratio [-50/50]	Welding Curent [A]	Arc Charact. [-10/10]	Depositio n rate (kg/h)	Theoretical deposition rate [kg/h]	Material loss [kg/h]	Dilution [%]	Bead height [mm]
20	70	700	0	183	0	6.26	7.50	-16%	8.85%	2.5
21	70	700	50	167	0	6.10	7.50	-19%	7.82%	2.65

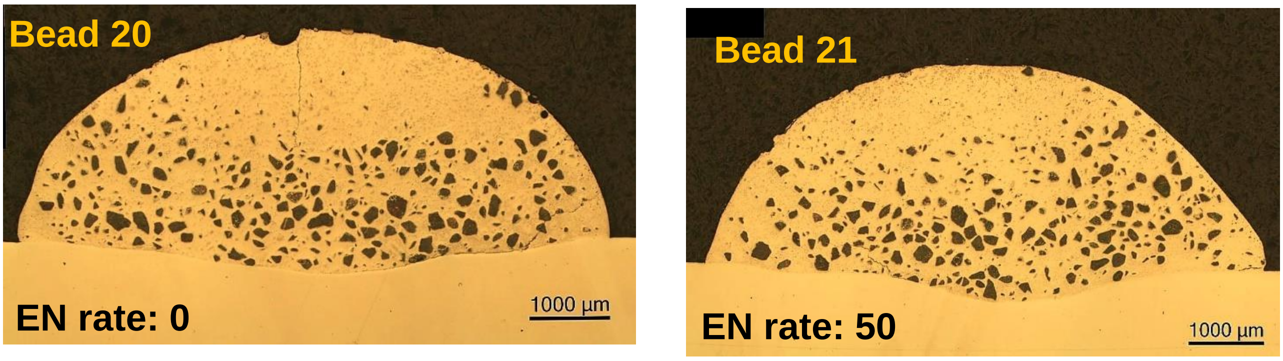


Figure 17: EN ratio results comparison. Analysis of bead 20 and 21. Etched with Murakami.

Once the EN ratio was increased for 50% the welding current necessary to melt the same wire feeding rate decreased from 183 to 167 A. The result tends to confirm the expectation. Less dilution, taller bead but inferior deposition rate (higher material loss). The FTC distribution did not show any apparent differences. Therefore, the FTC distribution must be controlled not only by the EN ratio, but also with other parameters, that, together, will input less energy making the carbide dissolution decrease.

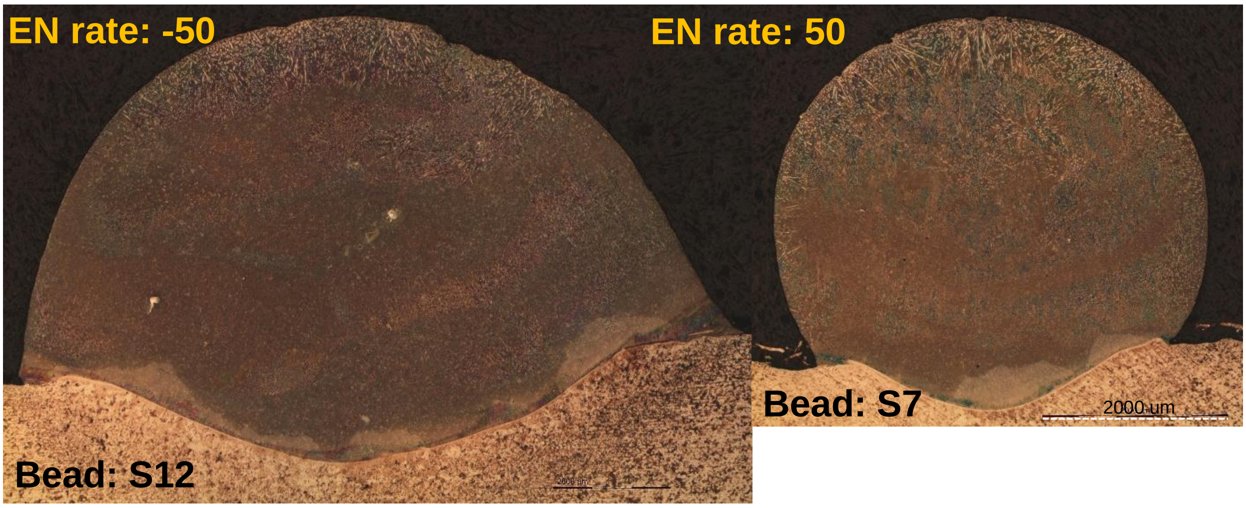


Figure 18: EN ratio comparison for FD 61 single beads same.

High EN ratios can bring also problems to the welding. Like shows figure 18, the bead wettability gets worse with this decreased energy input. While welding with a weaving pattern instead of stringer beads, this problem is severely reduced due to the mechanical spreading of the molten pool.

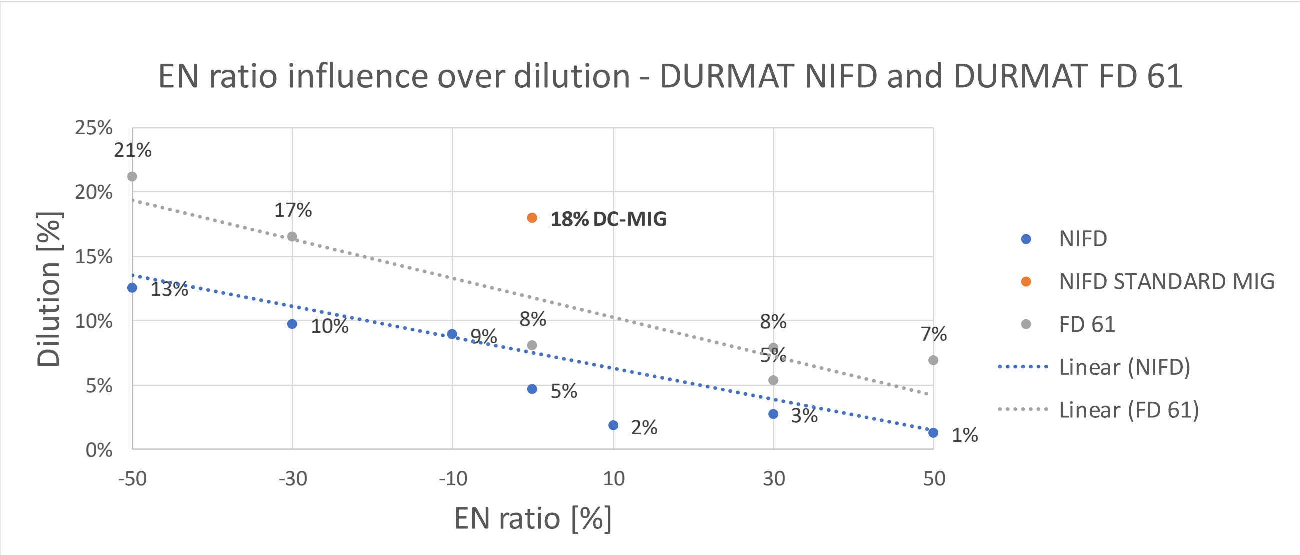


Chart 2: EN ratio influence over dilution for two hardfacing wires.

The chart 2 shows the relation between dilution and EN ratio, for DURMAT NIFD and for DURMAT FD 61 in the same chart. It can be compared also with the regular MIG process in the orange point (18% dilution). The minimal dilution occurred with the maximal EN ratio (EN ratio=50, dilution= 1%).

4.1.4 DURMAT NIFD – 1.6 mm

Follows bellow the proposed hardfaced plate in Figure 19, its welding parameters table, the microstructure and hardness profile.

Table 8: Welding parameters of DURMAT NIFD hardfaced area.

Wire	Welding speed [cm/min]	Wire feed rate [cm/min]	Torch angle [°]	EN ratio [-50/50]	Welding Curent [A]	Welding Voltage (V)	Arc Charact. [-10/10]	Arc adjusstment [-100/100]	Weaving speed [mm/min]	Weaving width [mm]	Deposition rate [kg/h]	Dilution [%]	Bead height [mm]	Bead width [mm]
DURMAT NIFD	7.2	480	0	50	195	16.7	0	0	1800	30	5	4.51%	4.01	36

Figure 19: DURMAT NIFD Hardfaced area.

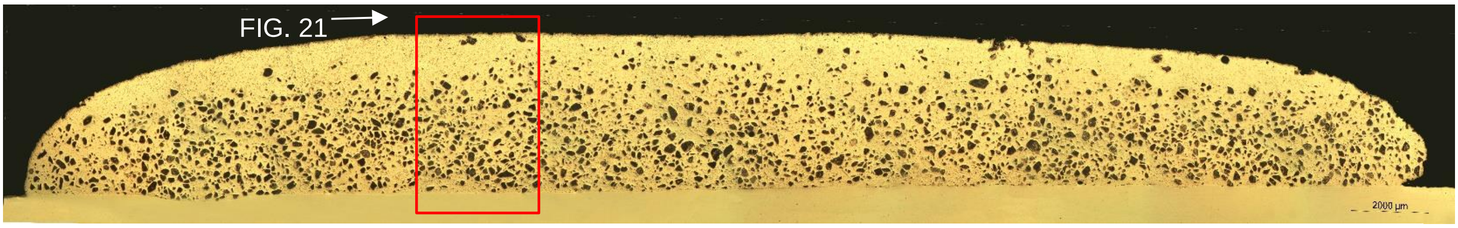
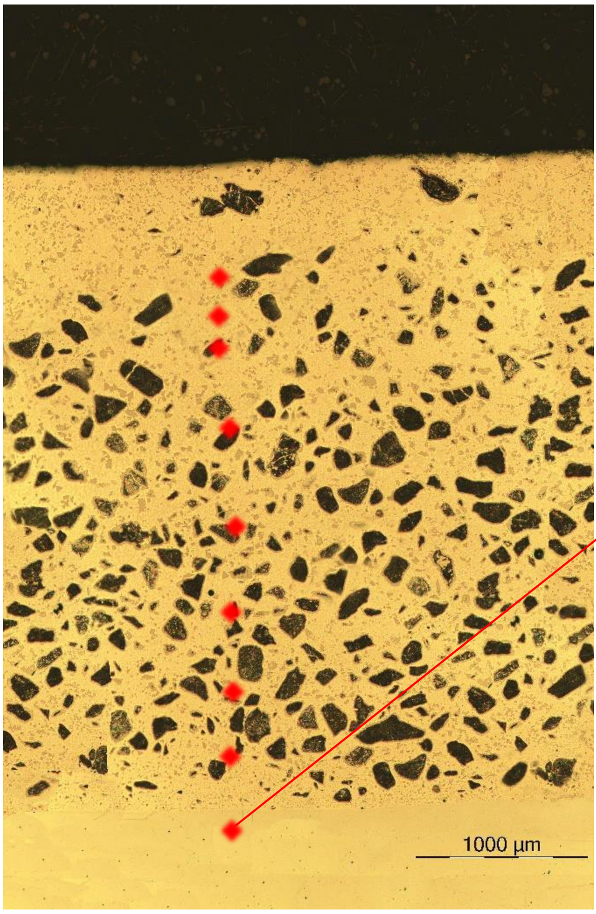


Figure 20: Cross section panorama of hardfacing weaving bead with DURMAT NIFD 1.6mm over S235 steel plate. Light microscopy 25x. Etched with Murakami. Scale bar: 2000 µm.



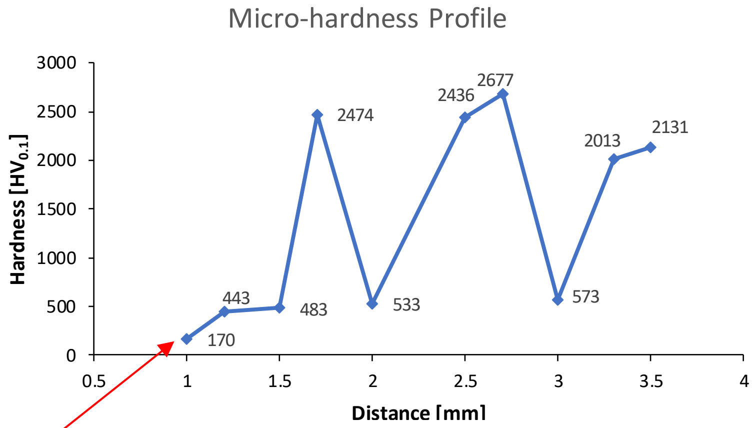


Chart 3: Vickers 0.1 Micro hardness profile according to the distance from the ground material. DURMAT NIFD.

Figure 21: Cross-section zoom of figure 20. Etched with Murakami. Scale bar: 1000 µm.

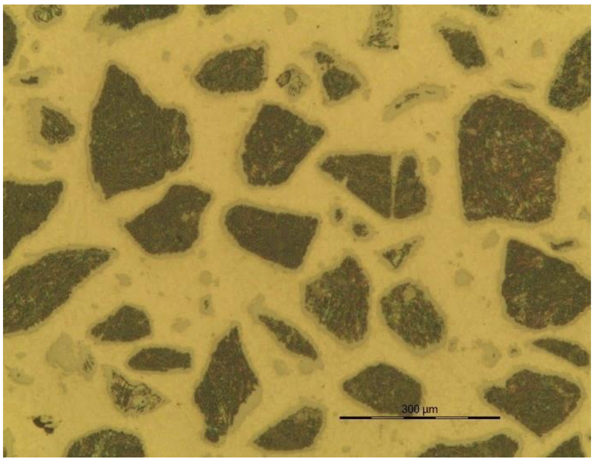


Figure 22: Light microscopy 100x. Etched with Murakami. Zoom of Fig. 21. Scale bar: 300 µm.

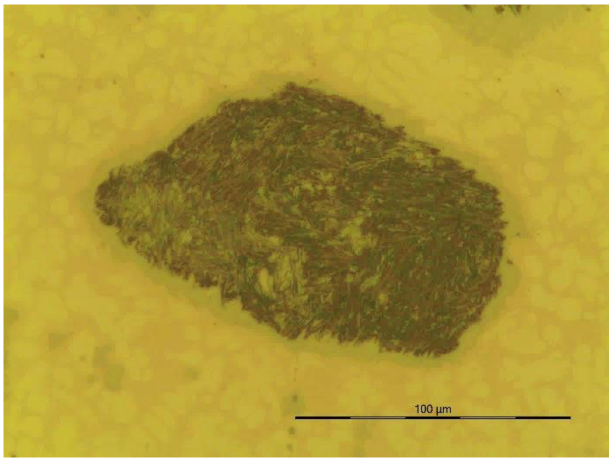


Figure 23: Light microscopy 500x. Etched with Murakami. The feather-like carbide microstructure. Scale bar: 300 µm.

4.1.5 DURMAT FD 61 – 1.6 mm

Follows bellow the proposed hardfaced plate Figure 24, its welding parameters table, the microstructure and hardness profile.

Table 9: Welding parameters of DURMAT FD 61 hardfaced area.

Wire	Welding speed [cm/min]	Wire feed rate [cm/min]	Torch angle [°]	EN ratio [-50/50]	Welding Curent [A]	Welding Voltage (V)	Arc Charact. [-10/10]	Arc adjusstment [-100/100]	Weaving speed [mm/min]	Weaving width [mm]	Deposition rate [kg/h]	Dilution [%]	Bead height [mm]	Bead width [mm]
DURMAT FD 61	7.2	430	0	50	170	20	0	30	1800	30	3	3.14%	4.75	38.9

Figure 24: DURMAT FD 61 hardfaced area.

Figure 25: Cross section panorama of hardfacing with DURMAT FD 61 1.6mm over S235 steel. Light microscopy 25x. Etched with Oberhofer. Scale bar = 2000 µm

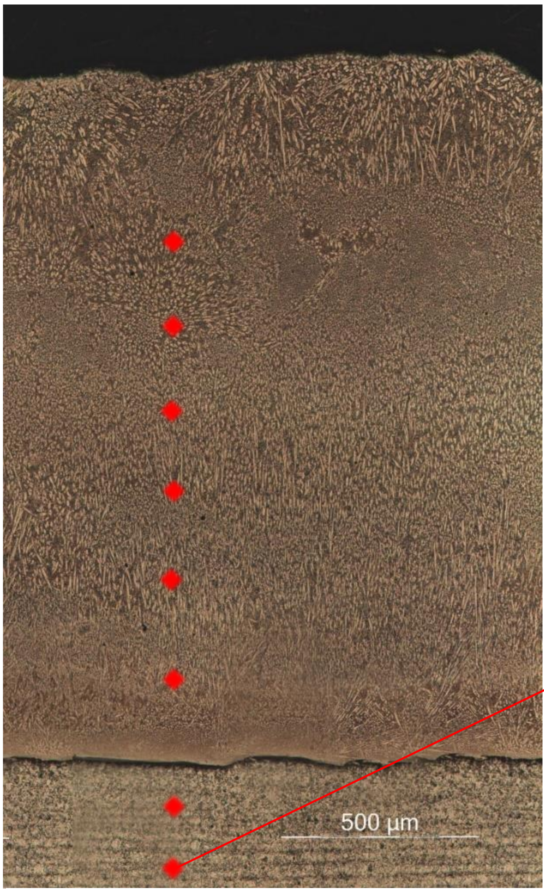


Figure 26: Zoom of the cross-section of figure 25. Etched with Oberhofer. Scale bar: 500 µm.

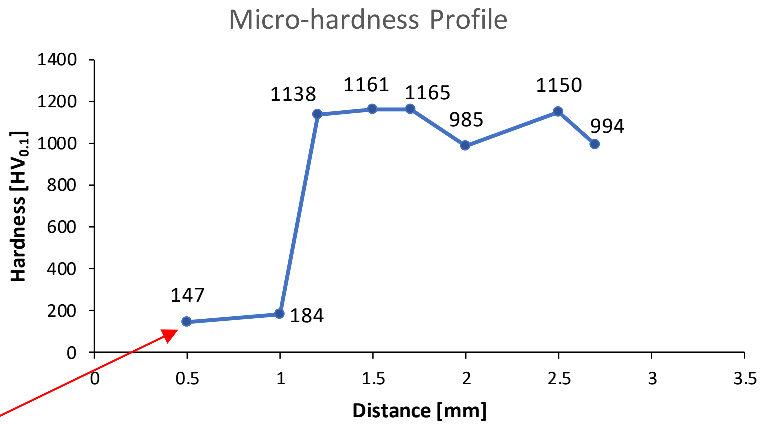


Chart 4: Vickers 0.1 Micro hardness profile according to the distance from the ground material. DURMAT FD 61.

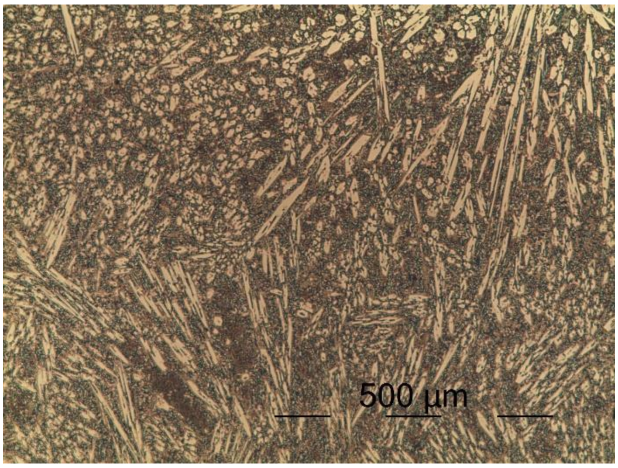


Figure 27: Light microscopy 100x. Etched with Oberhofer. Scale bar: 500 µm.

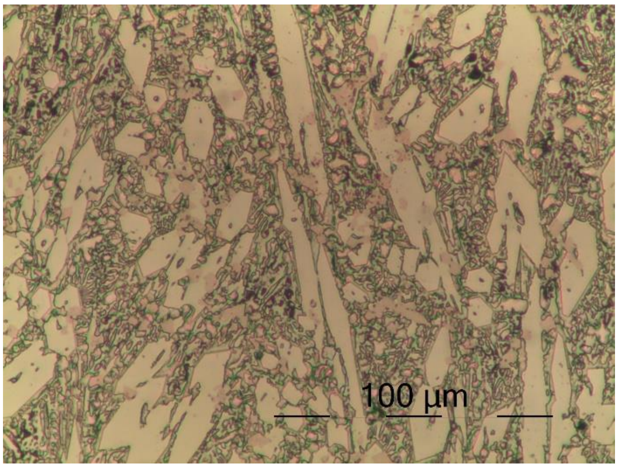


Figure 28: Light microscopy 500x. Etched with Oberhofer. Scale bar: 100 µm.

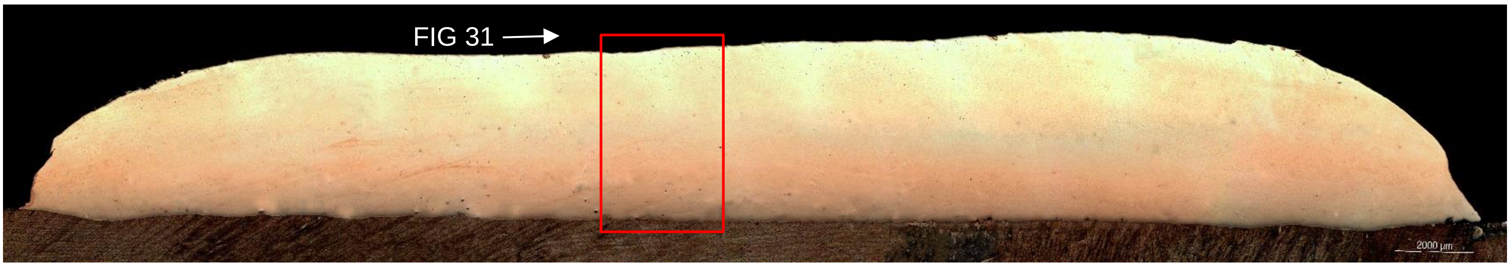
4.1.6 DUROLIT 6 – 1.6 mm

Follows bellow the proposed hardfaced plate picture, its welding parameters table, the microstructure and hardness profile

Table 10: Welding parameters of DUROLIT 6 hardfaced area.

Wire	Welding speed [cm/min]	Wire feed rate [cm/min]	Torch angle [°]	EN ratio [-50/50]	Welding Curent [A]	Welding Voltage (V)	Arc Charact. [-10/10]	Arc adjusstment [-100/100]	Weaving speed [mm/min]	Weaving width [mm]	Deposition rate [kg/h]	Dilution [%]	Bead height [mm]	Bead width [mm]
DUROLIT 6	7.2	470	0	50	215	17	-5	10	2000	30	3.8	1.86%	4.65	40.5

Figure 29: DUROLIT 6 hardfaced area.



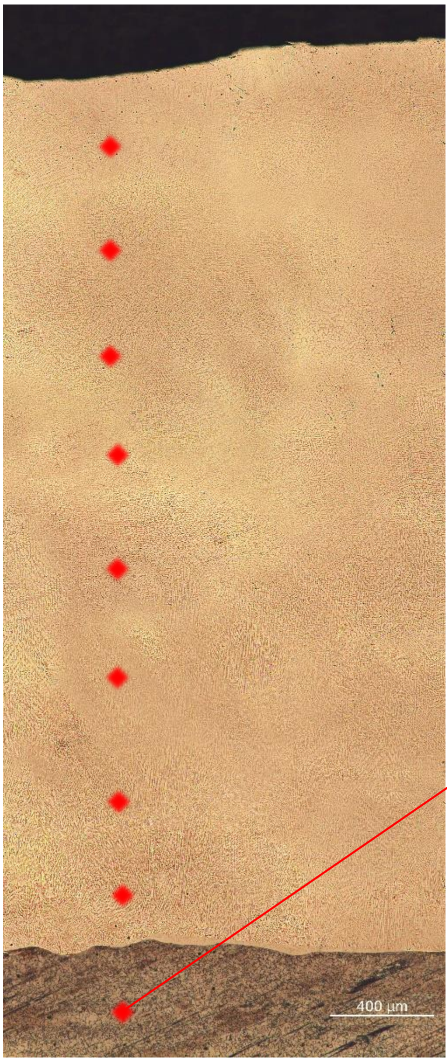


Figure 30: Cross section panorama of hardfacing with DUROLIT 6, 1.6mm, over S235 steel plate. Light microscopy 25x. Etched with Murakami.

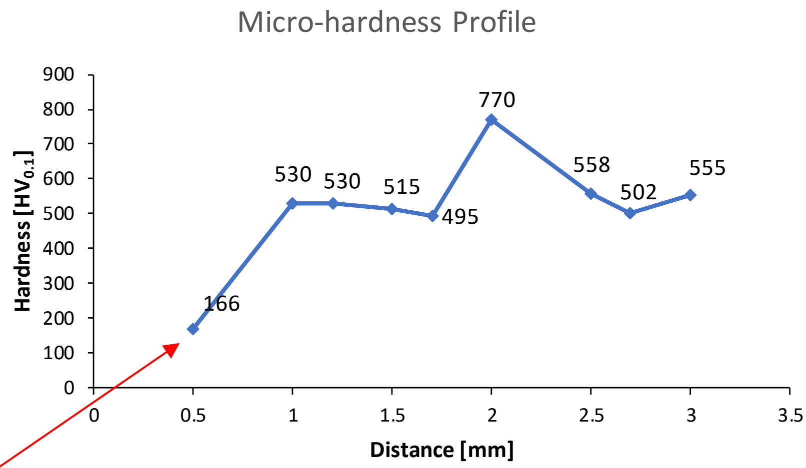


Chart 3: Micro hardness profile according to the specimen distance to the ground material.

Figure 31: Zoom of the cross-section of figure 30. Etched with Murakami. Zoom 100x. Bar scale 400µm.

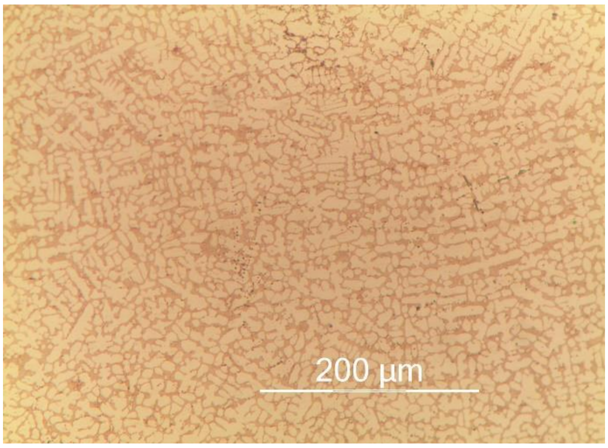


Figure 32: Light microscopy 200x. Etched with Murakami.

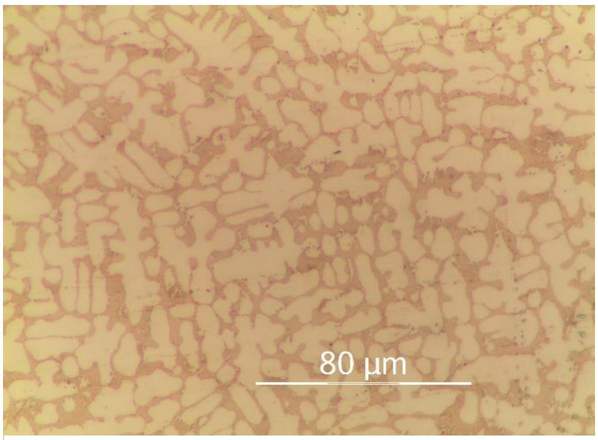


Figure 33: 500x. Etched with and Murakami.

4.1.7 Hardfaced pipes

After welding the weaving beads over steel plates, a closer to real industrial application specimen was defined: 7 inches outer diameter pipes comparing with oil industry tool joints hardfacing.

DURMAT NIFD – 1.6 mm

Figure 34: Hardfaced pipe. DURMAT NIFD.

Table 11: DURMAT NIFD hardfacing pipe test parameters.

Wire	Welding speed [cm/min]	Wire feed rate [cm/min]	Torch angle [°]	EN ratio [-50/50]	Welding Curent [A]	Welding Voltage (V)	Arc Charact. [-10/10]	Arc adjusstment [-100/100]	Weaving speed [mm/min]	Weaving width [mm]	Deposition rate [kg/h]
DURMAT NIFD	7.2	480	0	50	195	16.7	0	0	1800	30	5

4.1.7.2 DURMAT FD 61 – 1.6 mm

Figure 35: Hardfaced pipe. DURMAT FD 61.

Table 12: DURMAT FD 61 hardfacing pipe test parameters.

Wire	Welding speed [cm/min]	Wire feed rate [cm/min]	Torch angle [°]	EN ratio [-50/50]	Welding Curent [A]	Welding Voltage (V)	Arc Charact. [-10/10]	Arc adjusstment [-100/100]	Weaving speed [mm/min]	Weaving width [mm]	Deposition rate [kg/h]
DURMAT FD 61	7.2	430	0	50	170	20	0	30	1800	30	3

4.1.7.3 DUROLIT 6 – 1.6 mm

Figure 36: Hardfaced pipe. DUROLIT 6.

Table 13: Table 11: DUROLIT 6 hardfacing pipe test parameters.

Wire	Welding speed [cm/min]	Wire feed rate [cm/min]	Torch angle [°]	EN ratio [-50/50]	Welding Curent [A]	Welding Voltage (V)	Arc Charact. [-10/10]	Arc adjusstment [-100/100]	Weaving speed [mm/min]	Weaving width [mm]	Deposition rate [kg/h]
DUROLIT 6	7.45	470	0	50	219	14.4	50	0	1800	30	3.8

4.2 Material loss during welding

The literature about AC-MIG tends to say that the process brings together high material loss rates. This work showed that the OTC power source has a great stability control that allows this loss to be equal to normal MIG processes as Charts 5 and 6 presents. It is important to remember that flux-cored wires have always higher material loss once it is not a solid wire and so tends to lose more easily the inner powder while welding. DUROLIT 6 showed the same behavior of the bellow charts.

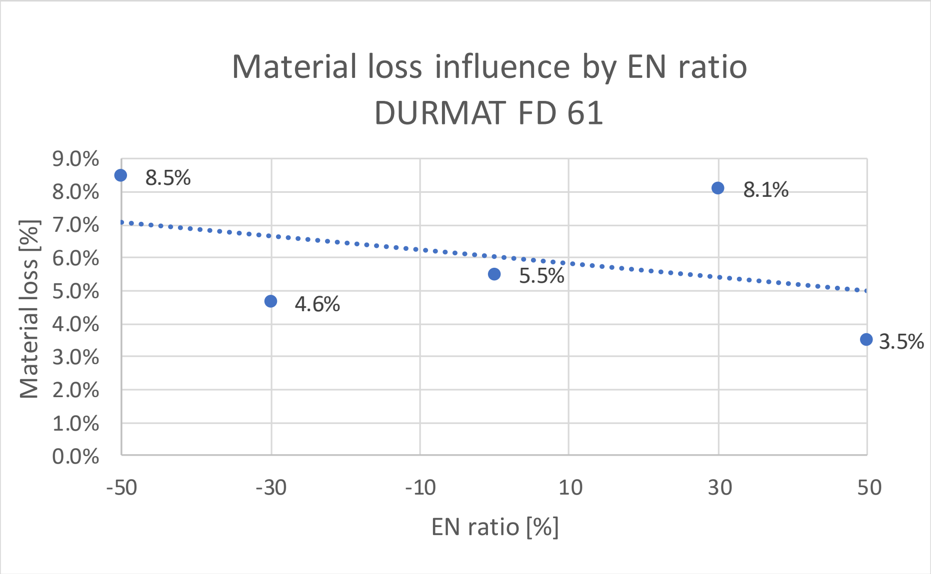


Chart 4: Material loss x EN ratio for DURMAT FD 61.

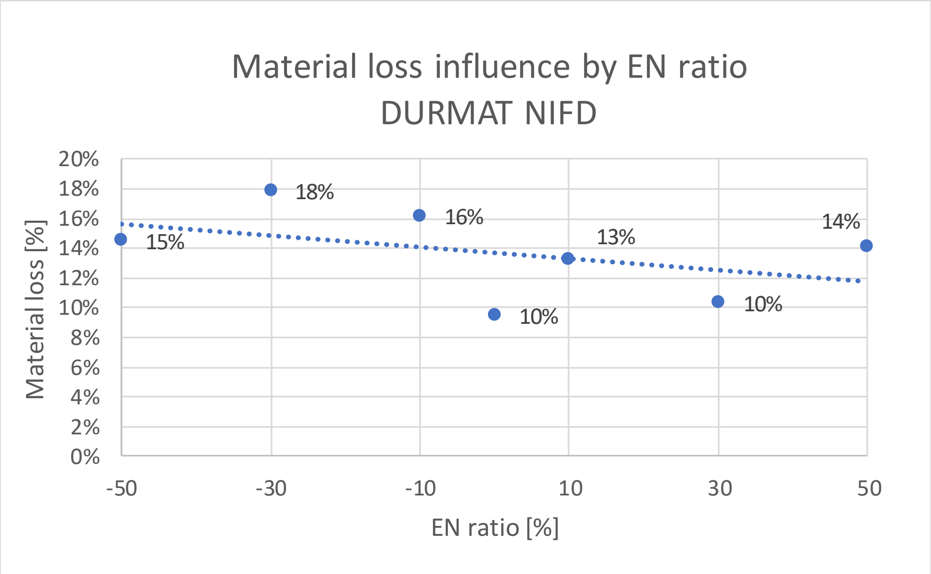


Chart 5: Material loss x EN ratio for DURMAT NIFD.

4.3 Abrasive wear resistance

As said in the literature revision, both ASTM G65 and G75 tests results aim a comparison with different materials for wear resistance approval and material selection.

4.3.1 ASTM G65 – Rubber-Wheel test

The rubber-wheel test result can be seen in charts 6 and 7, each one for a different media (Quartz and Corundum sand). The test type A is the most aggressive one, the resultant specimen after test can be seen in the Figure 37 and 38.

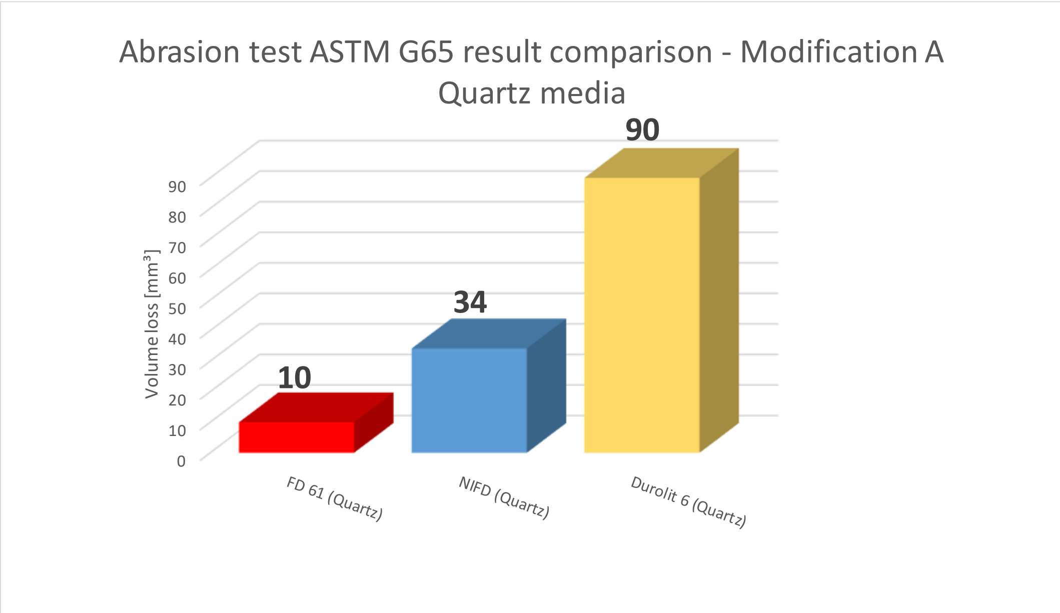


Chart 6: Abrasion resistance comparison. Quartz media.

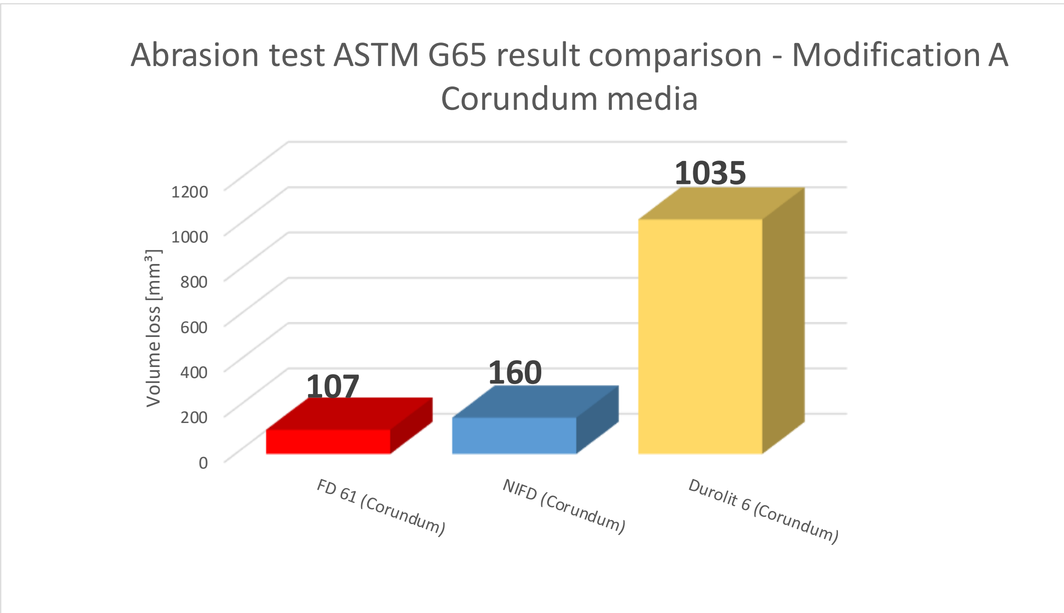


Chart 7: Abrasion resistance comparison. Corundum media.

In the DURMAT NIFD case the scratching pattern follows the sand flow direction, while the relatively soft NiCrBSi matrix is indented by the sand grains, that deform and posteriorly micro-cut the alloy until forming a path, the FTC keeps intact and prevents part of material removal.

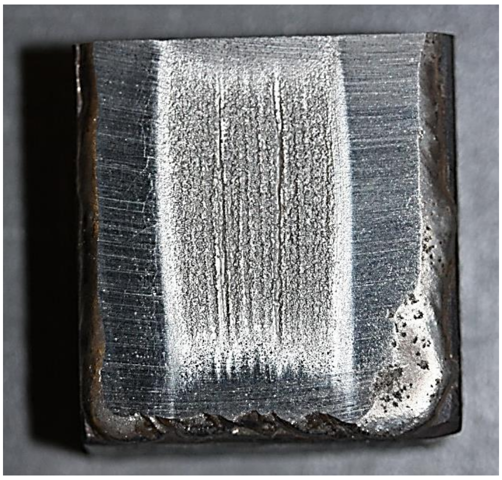


Figure 37: ASTM G65 NIFD specimen after test.

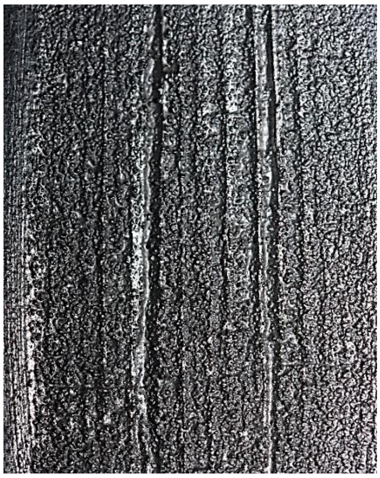


Figure 38: Scratched surface pattern of same specimen of figure 37 with 2x zoom.

4.3.2 ASTM G75 – Miller test

To confirm the hardfacing wear resistance and to give posterior works a comparison data, the ASTM G75 test was also performed. Two different slurries were used, one with Quartz and other with Corundum. The standard slurry composition was 150g of distilled water plus 150g of the hard particles. The data sheet key information is given in Table 14Table .

The instantaneous volume loss rate of both specimens in both slurries comparison can be seen in chart 10 in next page.

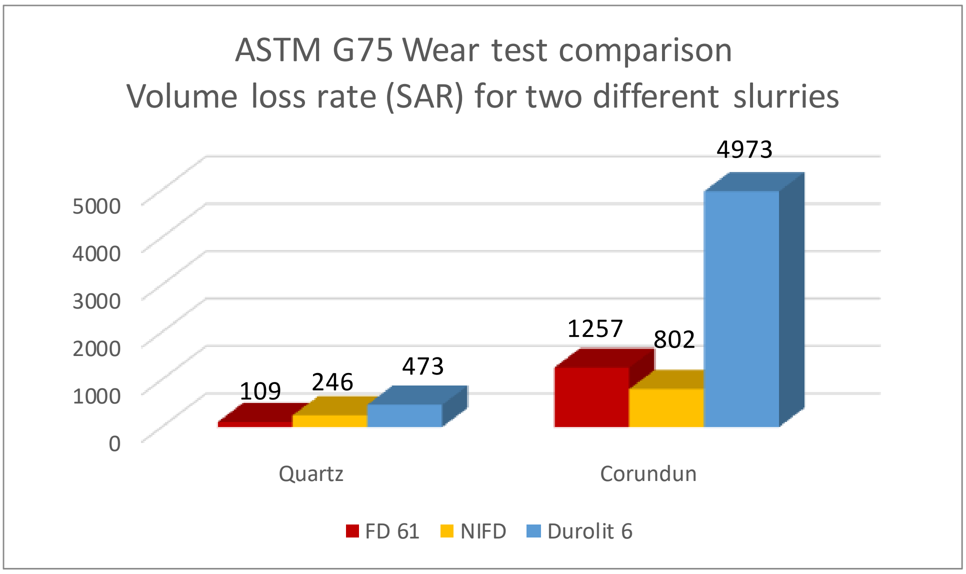


Chart 10: SAR number comparison between the wires and for two different slurries. The bigger the SAR number, less resistant to abrasive wear the material is.

Table 14: Hard particles key info.

Properties	Quartz Sand	Corundum
AFS/FEPA	54/-	-/F060
Average grain size [mm]	0.26	0.25
Specific gravity [g/cm^3]	2.65	4
Mohs Hardness	7	9
Typical chemical composition (weight%)		
SiO_2	99.82	1
Al_2O_3	0.1	95.65
TiO_2	-	2.4
Fe_2O_3	0.03	0.12
CaO	-	0.35
MgO	-	0.22

4.1 Deposition rates

For all wires, it was also measured the deposition rates ranges of application with a minimal welding energy that was previously set by means of bonding between welding layer and ground material.

The behavior seen was basically the decreasing of material loss during the welding within the increase of the deposition rates. The increase of deposition rates also showed an increase in dilution, so higher dilutions keep more material in the molten pool area. This doesn't mean that the microstructure will be homogeneous. Specially in the case of DURMAT NIFD where the FTC diffuse after a given temperature.

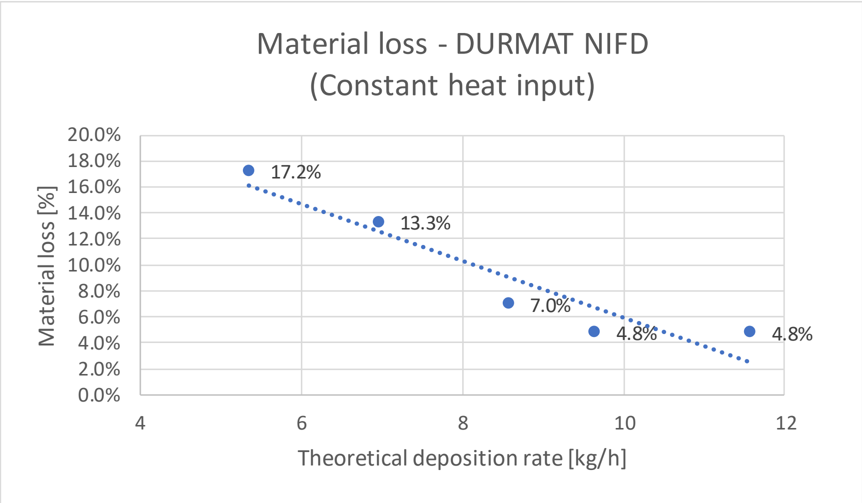


Chart 11: Material loss with increase of deposition rate. DURMAT NIFD.

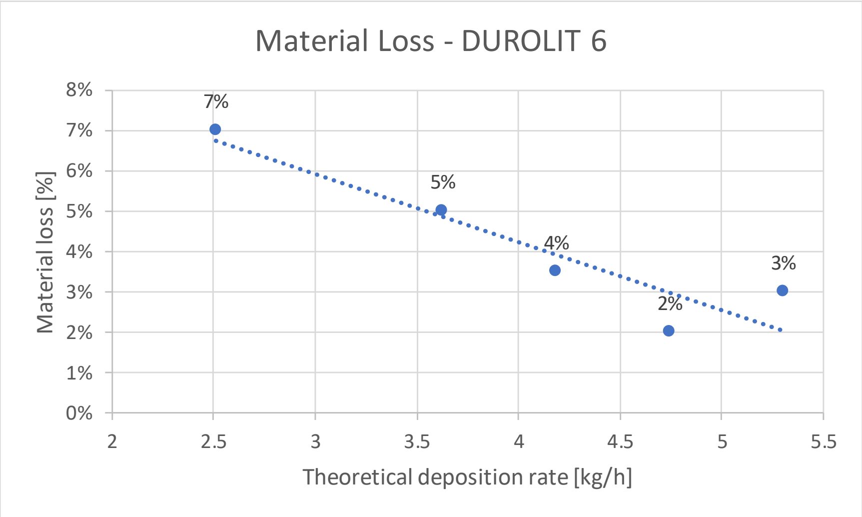


Chart 12: Material loss with increase of deposition rate. DUROLIT 6.

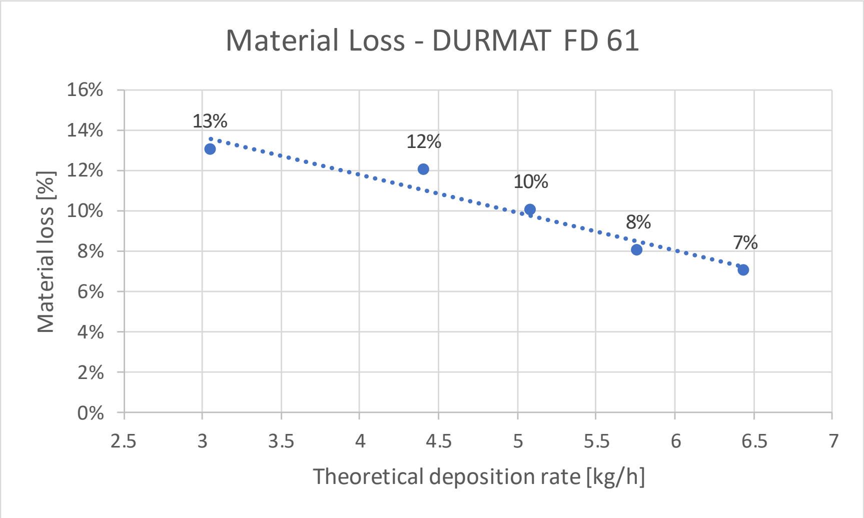


Chart 13: Material loss with increase of deposition rate. DURMAT FD 61.

5. Conclusions

The objective of this work was reached. High quality hardfaced deposits with low dilution using the required equipment and materials was achieve, according to the results presented. Showing high industrial usage for the AC MIG mode in the hardfacing area.

The process is a high-end gas metal arc welding alternative that can present high deposition rates and cladding quality like others new controlled short-circuit process. Even though the deposition rates increment bring together an increase in dilution and may cause additional material loss, the worst-case scenario still stands for better results than conventional MIG/MAG process. On the other hand, the best-case scenario confirmed results near to those normally seen in high complexity and more expensive technics like PTA-P.

The second objective of this work was the comparison of CMT and AC MIG with DURMAT FD 61. The discussion comes next.

5.1 Cold processes comparison - DURMAT FD 61

Once it was clear that both processes can deliver great hardfacing results of cladding quality and low dilutions due to its reduced heat input and controlled deposition method, the next comparison aspect to rank the processes is the maximal deposition rate limit. To explain the rise in material loss while increasing the deposition rate with CMT, a high-speed camera was used to analyze precisely the metal transfer. The slow-motion video cleared the doubts about this behavior, like shows Figure 39. [24]

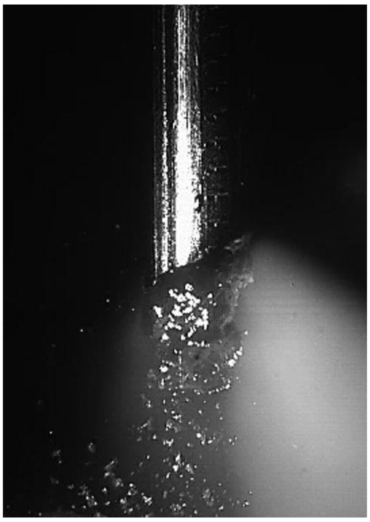


Figure 39: High speed recording frame of the moment when the flux-cored wire metal band is melted by the electric arc energy. The powder core flows to the molten pool. The material transfer is not as regular as in solid wires. [24]

Up to approximately 3.0 kg/h deposition rates with 4 to 5.5% of dilution were measured for DURMAT FD 61 with the controlled short-circuit. Higher wire feeding rates (along with higher current) showed to be not harmonically followed by the wire push and pull system. The wire retraction frequency, that is supposed to help the metal droplet detachment to be smooth, is too slow for wire feeding rates higher than 4.4 m/min. With further increase in the wire feed rate the process acts like an uncontrolled short circuit process, losing the process advantages.

The Chart 11 shows the U x I x T curve of this process. Unlike solid wire welding, after closing the circuit and pushing the wire up, the core does not melt, resulting in a unregular arc opening behavior, reducing the process advantages of low spatter, per example. It is important to say that the tests were made in the short-circuit range, spray transfers made both dilution and material loss higher for both processes.

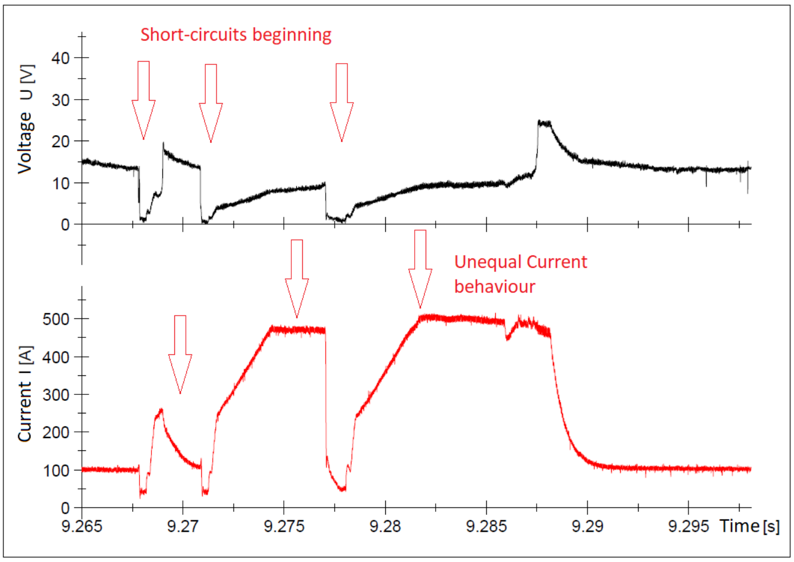


Chart 11: Voltage and Current x Time. Welding with Fronius CMT with DURMAT FD 61. The arc opening after short circuit shows a unregular behavior due to solid core electric interference. [24]

Table 15: Average result for both process with DURMAT FD 61

Deposition rate until **3** kg/h			
Material	**Process**	**Dilution [%]**	**Material loss [%]**
DURMAT FD 61	AC-MIG	4.50	13
	CMT	5.5	6.4

Deposition rate until **8** kg/h			
Material	**Process**	**Dilution [%]**	**Material loss [%]**
DURMAT FD 61	AC-MIG	8.50	7
	CMT	10.5	14.5

As shows the table 15, the average results for both process are into the acceptance criteria of dilution. Otherwise, for high deposition rates the CMT process seems to be inferior to the AC MIG. While the material loss is relatively stable when increasing the deposition rate for AC MIG, it does not happen with CMT. After 8 kg/h of deposition rate, the material loss grows exponentially, like explained in page 50, and the process is not anymore advised for this wire. Concluding that AC-MIG is more efficient for high deposition rates.

5.2 Travel angle

Even though it was expected less dilution with the forehand technique, the results showed similar levels for both forehand, backhand and perpendicular modes. Otherwise the FTC distribution with the forehand technique is far better and must be held as standard for the DURMAT NIFD. The intern concludes that, presumably, the reason for this difference may be due the higher molten pool “flux” caused by the arc pressure component in this technique, as schematize Figure 40. The red line in the figure shows the possible area which the FTC had been pushed up to and there lied when the pool solidified. It does not mean that all the FTC keeps there, but that the vortex may push particles, that normally would precipitate, up.

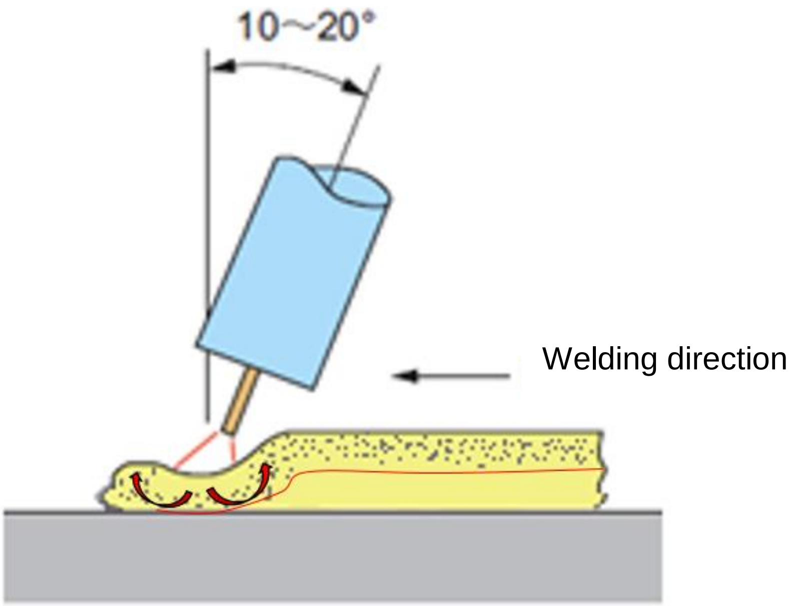


Figure 40: The arc pressure may form a vortex with enough strength to push the FTC particles up in the molten pool, that solidifies in this fashion.

5.3 Shielding Gas

Some beads showed lack of wettability which is a deleterious aspect that may cause welding failures like lack of fusion between overlaid beads. A different shielding gas could offer a hotter plasma that would increase the molten pool wettability, helping in this problem. Active gases like CO_2 and O_2 in small proportions (2-8%) might increase also the arc and metal transfer stability. It must be tested in the subsequent improvement of this work.

5.4 Arc characteristic

This parameter showed a good response that is useful for this application. Being able to reduce the heat input by means of spreading the arc allows the use of active gas mixture as shield gas, improving the wettability without compromising the dilution level.

5.5 EN ratio

The most important parameter for keeping the low heat input that allow us to call this process a “cold” welding. Against the previsions of literature, the power source controlled the material loss by spatter with great success.

The dilution control due to the heat input control gives this process a high sensible feature to small penetrations. Sometimes it can be too cold and bad bonding occurs. But decreasing a little bit the EN ratio or increasing the welding energy by means of arc adjustment gives a very sensible dilution control that can be compared to PTA-powder results.

The best results of dilution were achieved with 50% EN ratio, which was already expected since this is the “coldest” parameter.

5.6 Wear tests

The wear tests achieved the expected abrasion wear resistance ranking.

DUROLIT 6 showed the worst abrasion resistance. It was already expected once this alloy is made to work on high temperatures, in which the other alloys would not be able to give the same resistance to wear, and this ranking would probably revert. So, the comparison must be made with precaution.

DURMAT NIFD, as explained in page 26, is a composite made to resist against intense abrasion with big particles. Higher sand average grain size would put DURMAT NIFD as the most resistant flux-cored wire. As pointed before, wear mechanisms are complex and the best way to optimize the wear resistance is testing the wear with the specific application environment particle type and size, when possible.

5.7 Hardfaced pieces

Both pipes and plates hardface cladding showed good external appearance, with lack of great irregularities that would imply further corrections, showing once again the stability of the process even with flux-cored hardfacing wires.

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