A New Solution for Wear and Corrosion Protection: Alternating Current GMAW with Nickel, Cobalt and Iron Basis Flux-Cored Hardfacing Wires

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Abstract

Several relevant industrial areas of emerging countries' economic scenario, like oil drilling, agriculture and mining, rely on the hardfacing process to reach their procedure 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 increases the corrosion and, specially, the abrasive wear resistance of the component. Although, the current welding processes used for hardfacing are either too costly or lack in deposit quality. Some applications, especially in the emerging countries that usually struggle with equipment investment, would use from this cost benefit gap filling. In this work, a welding procedure was develop aiming to fulfill this market need with a new solution. The goal was to use an advanced GMAW (Gas Metal Arc Welding) process, not as expensive as LASER and PTA, along with high quality consumables to reduce hardfacing global costs while assuring good metallurgical deposit quality. To solve this challenge the use of alternating current (AC) GMAW process by an OTC Welbee P400 power source and flux-cored wires was proposed. Deposits of three typical hardfacing flux-cored wires of Ni, Co and Fe basis were made over 1" thickness S235 construction steel bars and over 7" outer diameter steel pipes. ASTM G65 and G75 wear resistance tests were carried out to evaluate each deposit abrasive wear resistance. The results demonstrated high possibility for industrial success in the hardfacing area. With outstanding outcomes of deposition rates up to 10 kg/h with less than 10% of dilution rates, surpassing "cold processes" like Fronius CMT in quality and material loss in the deposition rate upper limit. The fused tungsten carbides (FTC) in the Ni basis wire deposition presented homogeneous distribution along the welding bead. This behavior is due to the better heat input control compared to conventional GMAW processes, permitting the FTC to remain integer throughout the material transfer. After the overlay on both bars and pipes it was demonstrated that this process variant is feasible for industrial manufacture and repairing. Although it's metallurgical deposit quality still cannot match to PTA or LASER ones, the procedure here developed can fit the requirements of many vital applications, from hardfacing of sugarcane harvesting blades to oil drilling stabilizer tools, with reduced operational costs.

Key-words: *Cladding, AC-MIG/MAG, Fused Tungsten Carbide, stellite, PTA*

1. Introduction

The hardfacing process is an important part of many manufacturing and repairing operations. Relevant industries like oil drilling, agriculture and mining rely its process efficiency on hardfacing operations [1]. The deposition of hard phases embedded in a corrosion resistant matrix on parts and tools increases their operation limits and lifespan substantially. The hard phases, complex carbides like FTC (fused tungsten carbide) and B_4C, improve the wear resistance of components due to its microstructure. These hard phases embedded in the matrix present superior properties like hardness and fracture toughness, making it harder to job environment particles or fluids to break it and result in component material loss [2]. This is the abrasive wear behavior basic concept, which this kind of hardfacing attempts to combat. Once the microstructure of those phases is very important to guarantee the wear and corrosion resistance it must be held safe no matter the hardfacing process. In advanced welding process like PTA and LASER deposition the heat input is well controlled enough to not only keep these microstructures but also keep a low dilution rate between the coating material and the substrate. The distribution of the hard phases is also an important aspect.

Although, these welding processes are still not economically feasible for some application areas. This happens in emerging countries where entrepreneurs struggle with investment equipment financing. They tend to use conventional less costly welding process, increasing the final price due to lack of deposit quality and rework. The most used process for this at time is the GMAW process. Even though it has a better productivity than GTAW and almost achieve PTA deposition rates the high dilution rates decrease it profitability. GMAW state of art variants intend to fill this application gap. Controlled short-circuit GMAW, hot wire-assisted (HW-GMAW) and alternating current (AC-GMAW) are some of those high-end alternatives that might fill this opportunity gap. Both aims to provide a more sensitive heat input, making it possible to achieve better deposits quality with a not so complex and expensive welding process. This work proposes a hypothesis to fit the AC-GMAW process for the hardfacing of three different commercial relevant hardfacing materials: nickel basis with FTC, iron basis and cobalt basis.

Once the AC-GMAW is known to melt more material for the same energy input due to the change in polarity [3,4], it may result in lower dilution rates and keep the conventional GMAW deposition rate, improving the hardfacing quality and reducing the costs.

2. Materials and Methods

2.1. Materials

The first preliminary experiments were performed by single welding beads over a S235 steel bars (100 x 150 x 25 mm). The bars were grinded to remove the iron oxides coat and assure an even surface. Further industry application tests were performed by hardfacing mild steel pipes (7” OD, 1/2” thickness) with similar surface cleaning care.

Three different commercial flux-cored wires were tested, like table 1 presents, both from the same producer: DURUM Verschleiss-Schutz GmbH. All of them with 1.6 mm diameter. The shielding gas used was 100% argon, unless for the iron basis wire that had a self-shielding flux.

2.2. Equipment

Table 1: Flux-cored wire chemical composition.

Wire (ø 1.6 mm)	Chemical composition [weight %]									
	Ni	Fe	Co	C	Cr	W	B	Si	Mn	Nb
Nickel basis	Bal.	0.2	-	2.4	-	49.8	1.3	0.01	-	-
Iron basis	-	Bal.	-	5.2	22.0	-	1.0	1.3	0.4	7.0
Cobalt basis	-	2.0	Bal.	1.1	27.0	4.5	-	1.0	0.6	-

The power source used was an *OTC Welbee 400P*. A TBi water cooled gun with conventional contact tips, nozzles. Adequate rollers for flux-cored wire and PTFE liner were used to decrease feeding issues. The torch was connected to a CNC unit, that allowed three degrees of freedom. An additional turn table was used for the pipes hardfacing. The metallographic analysis was made by the following equipment: An automatic cut-off, an *Ahotec Vickers* hardness test, an *AXIO observer* light microscopy, a *Struers* automatic grinder/polisher.Wear resistance equipment following strictly the standards ASTM G65 (Rubber-Wheel test) [5] and ASTM G75 (Miller test) [6] were used to measure the wear resistance of the specimens. A very import equipment was the *Kern ABJ-NM* high precision balance with 0.001 grams sensitivity, critical to the abrasion test reliability.

2.3. Methodology

For the first attempts the steel bars were clamped on the CNC welding table and single beads were deposited over them. The power source synergic programs were tested, and the program *Al* 99 showed the best macro results. After that, primary welding parameters influence over bead quality were analyzed. Contact tip to work distance (CTWD), travel angle and gas flow were set for each kind of wire. Electric parameters were later studied with a deeper analysis, seeking the application limits and its influence over dilution rate, material loss, deposition rate and microstructure of the hardfacing. The deposition rate was first theoretically calculated, as Equation 1 shows, and them empirically measured by the difference of the specimen weight before and after welding. The material loss was approximated by the difference of both calculated deposition rates.

$$D_t = M \times V_w \quad (1)$$

D_t – Theoretically deposition rate [kg/h]
M – Mass of one meter of wire [kg/m]
V_w – Wire feeding speed [m/h]

The dilution rate was evaluated by the areas quotient method like Equation 2 and Figure 1 explain. Due to the dilution dispersion over the bead and the calculation inherent errors the dilution rates results are approximated to the nearer upper integer number, demonstrated in Equation 2. The software used to measure the dilution rate was the opens source *Fiji.*

$$D = \frac{A_2}{A_2+A_1} = \frac{7609}{7609+131306} = 5{,}46 \sim 5\%\ dilution \qquad (2)$$

D – dilution rate [%]
A_2 – Area under the substrate line. [pixels]
A_1 – Area above the substrate line. [pixels]

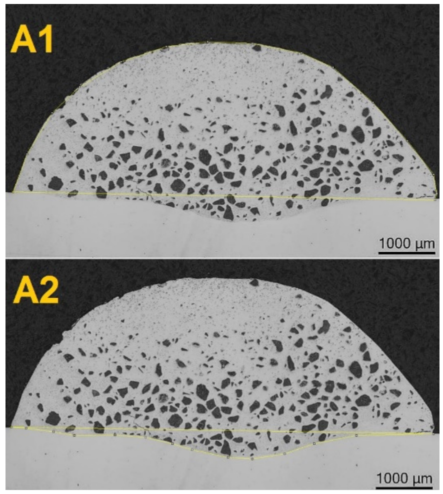

Figure 1: Area methods for dilution rate example.

3. Results and Discussion

The AC-GMAW process has special electric parameters options like EN ratio and electric arc characteristic. This more complex equipment required special care in the experiment matrix. To evaluate the influence of the process parameters on hardfacing with the three wires each parameter was changed at time and comparison between the results were evaluated. The results as shown with a division per parameter that showed more influence in the studied aspects: deposition rate, dilution rate, microstructure and material loss.

3.1. Travel angle

The first parameter that showed influence on the microstructure of the deposit was the travel angle. An angle between 10 to 20° with a forehand welding direction showed better FTC distribution for the nickel basis wire. The Figure 2 shows the expected difference of results in conventional GMAW process when changing the travel angle from forehand to backhand.

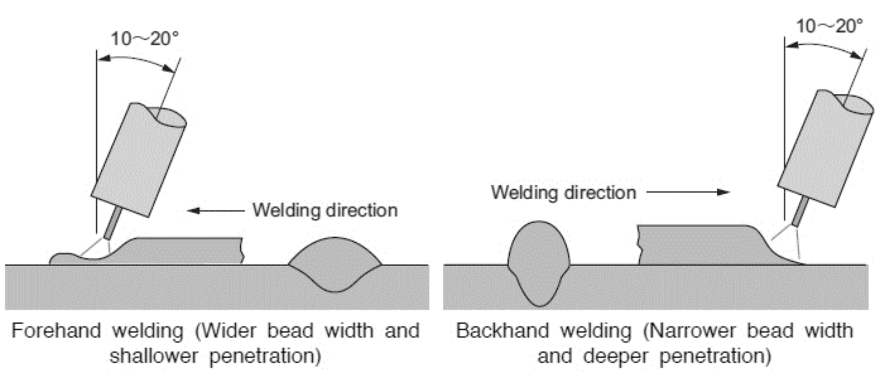

Figure 2: Schematic representation of travel angles generalized effect on the bead.

The Figure 3 and 4 bring the bead cross section after macroscopy analysis treatment. The differences of FTC distribution and bead shape are notorious and respect the effect showed in the Figure 2. Once the FTC are better distributed in the case of forehand technic that was kept for the other tests.

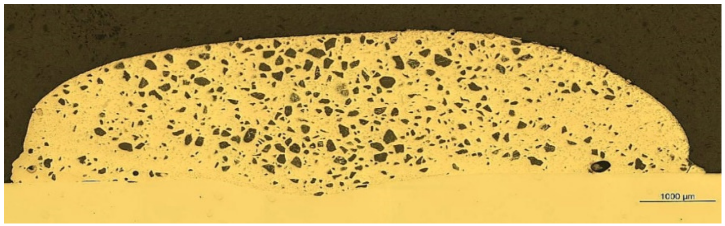

Figure 3: Forehand welded bead with 15° angle. FTC is spread on the top. Etched with Murakami.

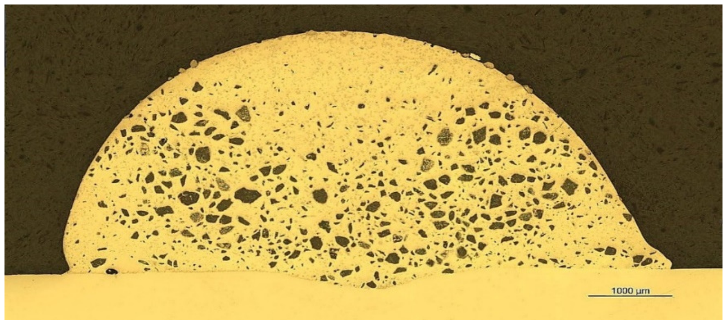

Figure 4: Backhand welded bead with 15° angle. Lack of FTC on top. Etched with Murakami.

3.2. EN ratio

The EN ratio parameter is the method to control the ratio between current polarity. It means not only the time in which the wire is the negative pole (straight polarity) but also the intensity of the current at this moment. Higher EN ratios were expected to reduce the dilution rate. The results confirm this behavior for both wires. The FTC distribution, however, showed only minor improvement like Figure 5 shows.

High EN ratios can also bring problems to the welding. 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. 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 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 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.

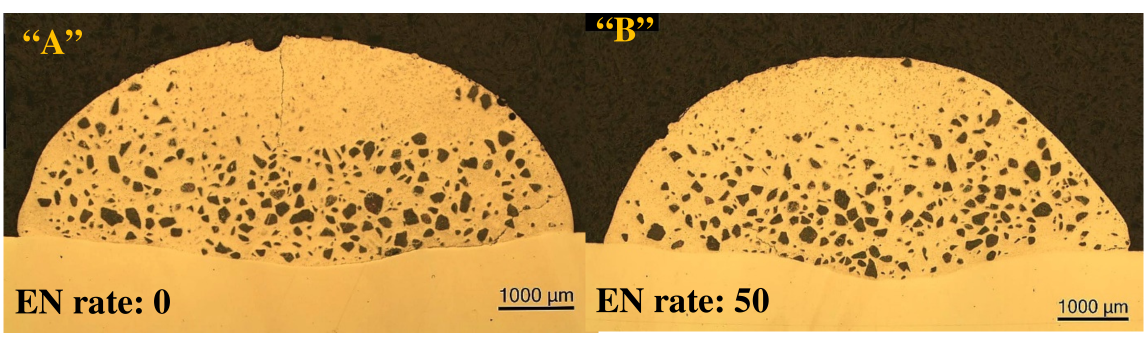

Figure 5: EN ratio results comparison. Analysis of bead A and B. Etched with Murakami.

3.3. Arc characteristic

This parameter ranges from -10 to +10. According to the power source company (OTC) 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. Seeking to spread more the energy, and, thus, reduce the heat input, an arc characteristic of +10 was proposed for comparison. This power source control changes adjusts the process frequency. Higher rigidity is reach by increasing the frequency, which also decrease the arc height. A more spread arc resulted in less dilution. Another factor is that the arc instability increases when using softer arc shapes. 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. Although, like shows Figure 6, this parameter works as fine tuner of energy input, and other parameter like EN ratio have much greater impact of the bead characteristics.

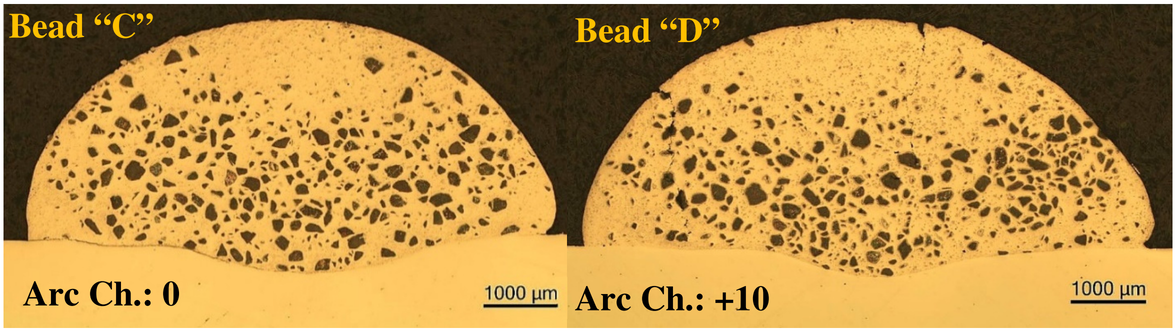

Figure 6: Comparison between beads “C” and “D” due to arc characteristic parameter rise. Etched with Murakami.

3.4. Abrasive wear resistance

The abrasion wear resistance tests showed the expected results for both wires. Concluding that the microstructure achieved with the AC-GMAW was reliable. The wear tests achieved the expected abrasion wear resistance ranking. The Cobalt basis wire 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. The Chart 1 shows the results for ASTM G65 and Chart 2 for ASTM G75.

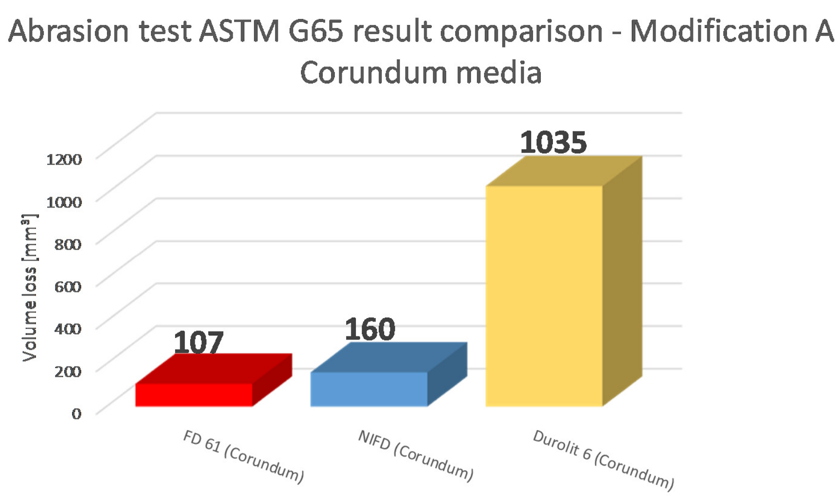

Chart 1: Volume loss difference of the three alloys. FD 61 (iron basis), NIFD (nickel basis), Durolit 6 (cobalt basis).

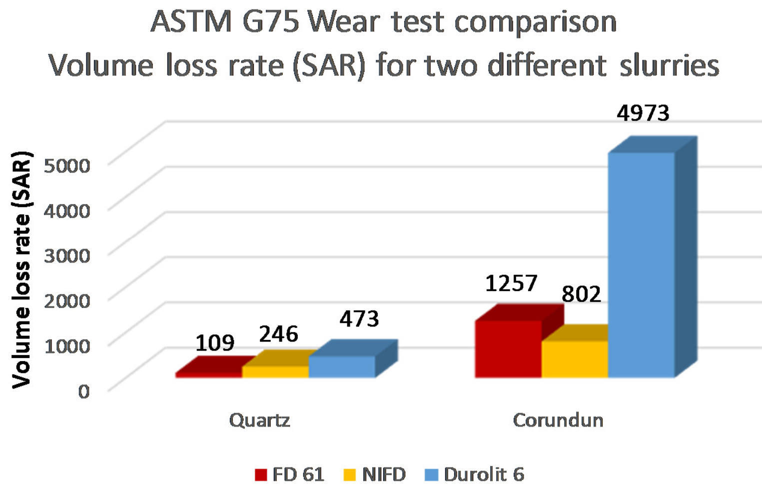

Chart 2: Volume loss difference of the three alloys.

The nickel basis wire is a composite made to resist against intense abrasion with big particles. Higher sand average grain size would put this wire 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. The initial wear rate phase with a nickel basis plus FTC coating is also higher due to the smaller presence of FTC on the very top, different than the other alloys in which the hard phases are nucleated even more in the border areas like seem in the iron basis wire. For longer and more aggressive wear phenomena the nickel basis would show superior wear resistance than all other alloys.

Figure 7 shows the specimen of the wear resistance ASTM G65 test. A scratching pattern made along the sand flow direction, while the relatively soft NiCrBSi matrix (≈530 $HV_{0,1}$) is indented by the sand grains, that deform and posteriorly micro-cut the alloy until forming a path, the FTC (≈2300 $HV_{0,1}$) is kept intact and prevents part of material removal.

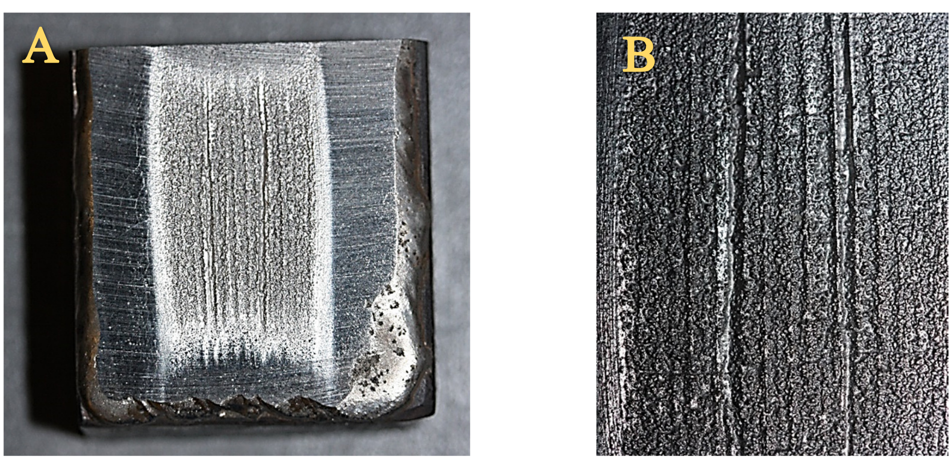

Figure 7: (A) Specimen after G65 abrasion test. (B) Zoom of specimen “A”.

3.5. Material loss

AC-GMAW usually is referred as a process that 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 3 and 4 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. Considering the measurements errors and small data acquired the material loss is very little influenced by the EN ratio or not influenced at all as chart 3 and 4 show.

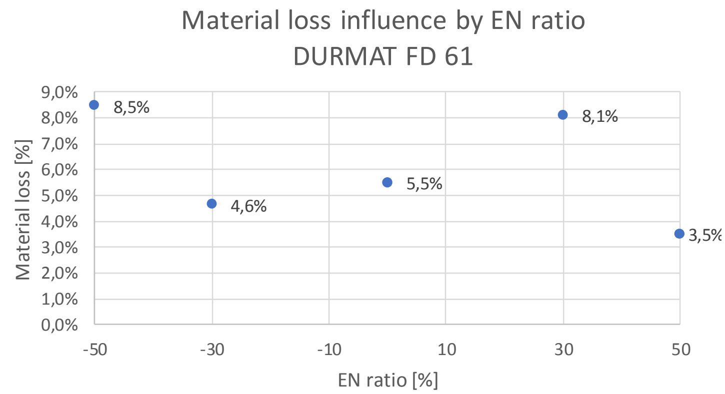

Chart 3: There is no evidence that the material loss is influenced by the EN ratio.

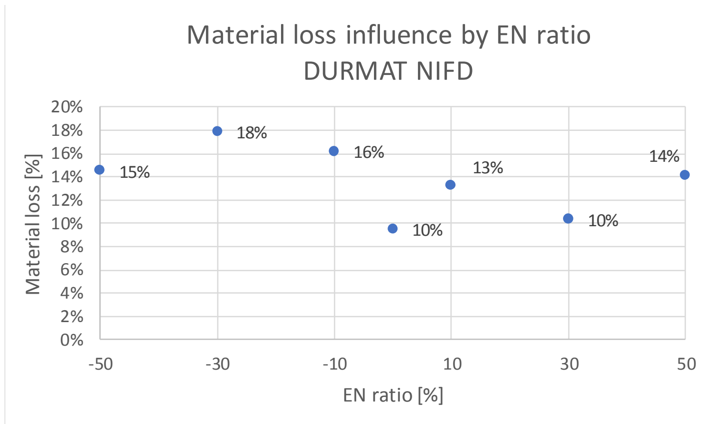

Chart 4: The EN ratio for the nickel basis wire also did not bring evidence that influences the material loss.

3.6. Practical validation

Figure 8 shows the hardfacing results of the 7" pipes, made to evaluate the results in a practical situation. The results presented the macroscopically quality within the visual acceptance criteria.

Figure 8: Three 7" pipe sections hardfaced with three diferente flux cored wires.: (A) Nickel basis, (B) Iron basis, (C) Cobalt basis. Scale: 30 mm.

3.7. Micrography analysis

Both flux-cored wires were used to hardface a steel bar according to the methodology. These bars were cut and the micrography are presented below. The Figure 9, 10 and 11 bring the nickel basis wire. The NiCrBSi matrix The results were compatible with the expected. The FTC distribution is still not homogeneous but already better than conventional welding methods.

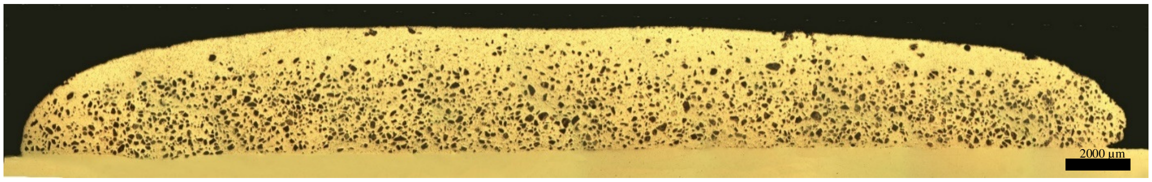

Figure 9: Cross section panorama of hardfacing bead with DURMAT NIFD 1.6 mm over S235 steel plate. Light microscopy 25x. Etched with Murakami. Scale bar: 2000 µm.

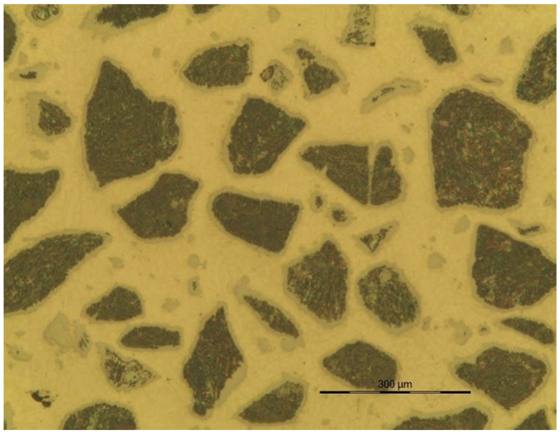

Figure 10: Light microscopy 100x. Etched with Murakami. Zoom of Fig. 9 Scale bar: 300 µm.

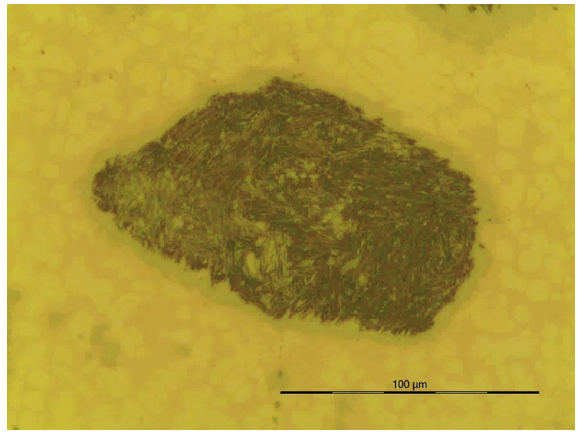

Figure 11: Light microscopy 500x. Zoom of Figure 10. Etched with Murakami. The feather-like carbide microstructure. Scale bar: 300 µm.

The heat input was controlled enough to allow the feather like tungsten carbide structure to resists through the electric arc. The Figure 9, 10 and 11 shows the iron basis hardfacing micrography.

Figure 12: Cross section panorama of hardfacing with DURMAT FD 61 1.6mm over S235 steel. Light microscopy 25x. Etched with Oberhofer. Scale bar = 2000 µm

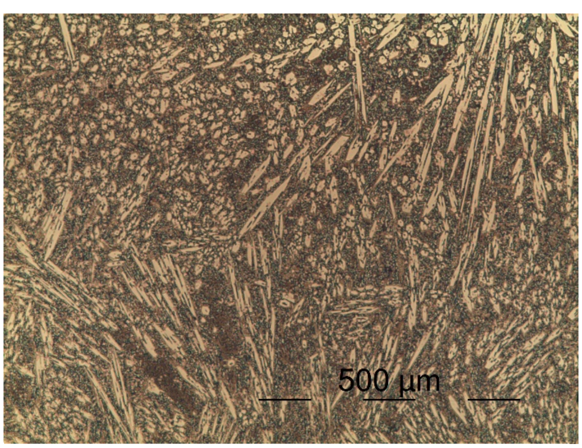

Figure 13: Light microscopy 100x. Etched with Oberhofer. Scale bar: 500 µm.

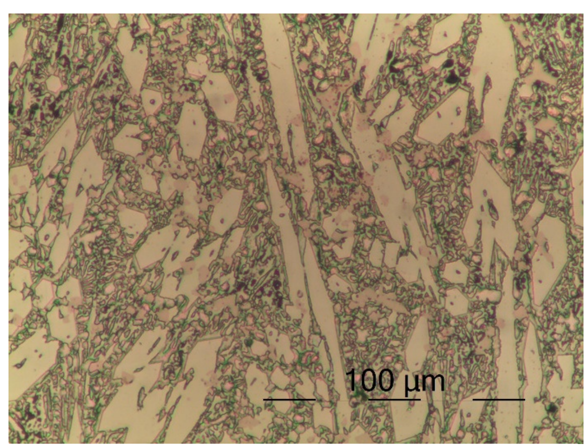

Figure 14: Light microscopy 500x. Etched with Oberhofer. Scale bar: 100 µm.

The cracks in Figure 12 are considered usual in this kind of hard faced overlay. The lack of ductility due to the hard phases did not allow the stress caused after the bead cooling to dissipate by deformation means. The chromium carbide spikes (≈1150 $HV_{0,1}$) seen in Figure 13 and 14 form together with Niobium fine carbides the hard phase.

The cobalt basis hardfacing micrography is showed in Figures 15, 16 and 17.

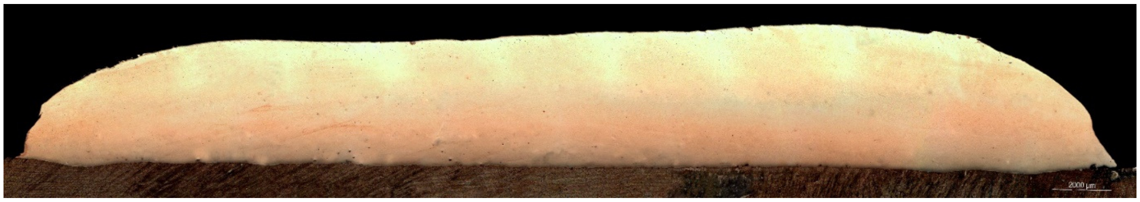

Figure 15: Cross section panorama of hardfacing with DUROLIT 6, 1.6mm, over S235 steel plate. Light microscopy 25x. Etched with Murakami.

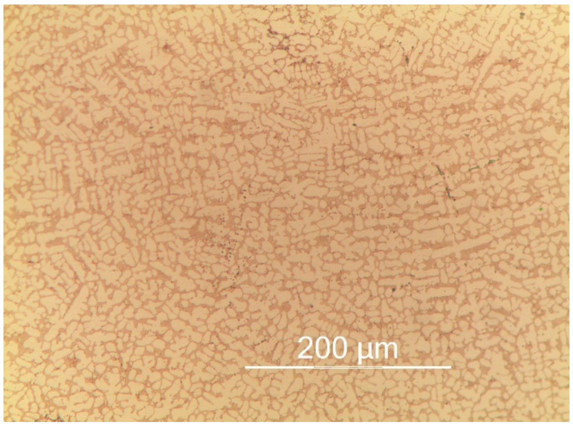

Figure 16: Light microscopy 200x. Etched with Murakami.

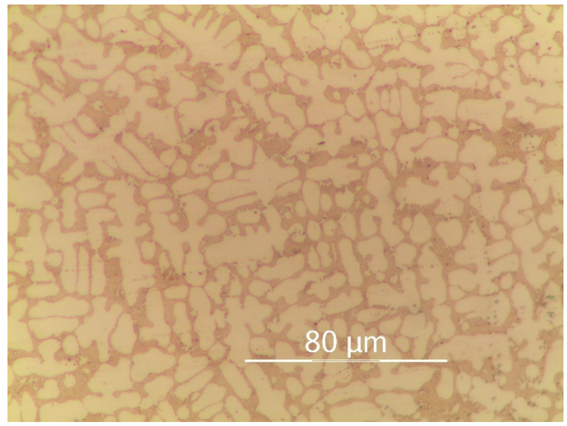

Figure 17: 500x. Etched with and Murakami.

The Durolit 6, cobalt basis wire, micrography showed the expected result: cobalt rich matrix with hard phases, dendrites, dispersed.

4. Conclusion

The research showed the that the AC-GMAW process can deposit hardfacing coatings with high deposition rates, reducing costs for three highly used different flux-cored wires while reaching a quality gap in the industry. The process is highly recommended for hardfacing applications in the medium level of equipment investment and quality requirements.

5. Acknowledgments

This project was made in a partnership between the Mechatronics and Welding Institute: LABSOLDA, the STAR laboratory of the HSNR and sponsored by the company DURUM Verschleiss-Schutz GmbH.

6. References

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