ANALYSIS OF TYPES OF HARDFACING APPLIED BY WELDING IN COMPONENTS USED IN SUGAR/ALCOHOL INDUSTRY

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Abstract. The Brazilian sugar/alcohol sector presented expressive growth in recent years. However maintenance cost is high due to metallic losses by wear. This paper studies the application of hardfacing by flux cored arc welding on the wear resistance of sugarcane shredder knives comparing laboratory and field-test results. Four types of consumable were used: three selfshielded flux cored wires of diameter 1.6 mm of alloys FeCrC, FeCrC+Nb and FeCrC+Ti and a covered electrode of FeCrC alloy of diameter 4.0 mm. The base metal is SAE1020 steel. Test specimens were evaluated using rubber wheel abrasion tests (ASTM G65). Sugarcane shredder knives hardfaced in the same welding conditions were also tested on a shredder in an alcohol distillery. Wear evaluation was by mass loss. The flux cored wires were welded in short-circuit transfer mode with the same current and voltage values. The wire with Nb had the highest wear resistance in laboratory test but due to cracks and spalling had the least wear resistance in field test. The FeCrC and FeCrC+Ti wires presented the worst results in laboratory tests and the best results in field test, respectively. In comparison with the covered electrode, the FeCrC+Nb wire presented similar performance in laboratory and the FeCrC+Ti wire presented similar performance in field tests

***Keywords**: Hardfacing, Wear resistance, Flux cored wire, Sugar/alcohol industries*

1. INTRODUCTION

The Brazilian sugar/alcohol industries presented great expansion in recent years due to the increase in consumption of ethanol locally and the targeted increase of usage of biofuels in USA, Europe and Japan. Brazil is the world's greatest sugar producer and the second greatest producer of ethanol. Material losses due to wear represents a significant cost in operation of sugar/alcohol industries, where wear of implements is great and service life of the components is short.

It is verified that the equipment which are most critical in terms of wear by abrasion are: the feeder table, the leveler, the rollers, the bearings, the shredder knives, the shredder hammers and the mills. While the greater part of these equipments can be remanufactured between harvest, the shredder knives and the shredder hammers due their short service life are responsible for stoppage during harvest for their substitution. These tools are recovered by welding of hardfacing using different processes, techniques and consumables to replace the metal lost in service.

Traditionally in Brazilian industry the application of hardfacing has been either manually by shielded electrode process or automatically by submerged arc process when the geometry or dimensions are favorable. Due to a greater productivity when compared to the former and a greater adaptability in relation to the latter, flux cored arc welding has became an important alternative with a great variety of consumables for different applications of hardfacings.

In this study, three types of selfshielded flux cored wires of FeCrC alloy indicated by the manufacturer for applications in sugar/alcohol industries for shredder knives and hammers were used. The difference between the wires is the percentage of carbon, chromium, silicon and manganese, besides niobium, titanium and molybdenum. An electrode of the traditional covered electrode process was also used.

The objective of this study is to evaluate the abrasion wear resistance of consumable applied by welding using the Rubber Wheel Abrasion Testes in laboratory and for comparison in working conditions in the form of hardfacings of sugarcane shredder knives.

2. MATERIALS AND EXPERIMENTAL METHODS

A multiple process electronic welding machine adjusted for constant voltage made of flux cored arc welding and constant current mode of covered electrode process was used. Four consumables of FeCrC alloys were used: a covered electrode of diameter 4.0 mm and three selfshielded flux cored wires of diameter 1.6 mm of different percentages of iron, chromium, carbon, silicon and manganese, beside niobium and titanium and molybdenum. These consumables will be named ER1, FeCrC, +Nb and +Ti respectively. Table 1 shows the range of hardness obtained by the first weld layer as well as the chemical composition of the consumables given by the manufactures.

For the Rubber Wheel Tests the weld was a single layer with beads of 150mm length (five weld beads per hardfacing) on SAE 1020 steel plates of 12.7 x 50.8 x 200mm. Five plates were welded with each consumable. The test specimens for wear evaluation were obtained from the central region. Table 2 shows the welding parameters used. For flux cored arc welding, the up-down inductance, wire feed rate (Valim), weld speed (Vsold) and reference voltage (Ur) were maintained constant, in order to obtain metallic transfer in short-circuit mode.

Table 1. Consumable data (selfshielded flux cored wires and covered electrode)

Electrode Type	**Hardness HRc**	**Chemical composition(%)**								
		C	**Cr**	**Mn**	**Si**	**S**	**P**	**Nb**	**Mo**	**Ti**
FeCrC	59-61	4,110	23,100	0,520	0,200	0,000	0,000	-	-	-
FeCrC+**Nb**	57-64	4,500	22,000	0,500	0,600	0,002	0,001	6,500	-	-
FeCrC+**Ti**	52-64	1,800	7,500	0,840	0,500	0,018	0,027	-	1,500	5,260
ER1	58-63	5,100	44,00	0,750	1,250	0,025	0,035	-	-	-

Table 2. Welding parameters used to obtain the test specimens.

<table>
<tr><th>Wire type</th><th>D (mm)</th><th>V_{alim} (m/min)</th><th>V_{sold} (cm/min)</th><th>U_r (V)</th><th>P (mm)</th><th>DBCP (mm)</th><th>I_{des} (A)</th></tr>
<tr><td>FeCrC</td><td rowspan="3">1,6</td><td rowspan="3">10</td><td rowspan="3">50</td><td rowspan="3">28</td><td>6</td><td>35</td><td>270</td></tr>
<tr><td>FeCrC+Nb</td><td>6</td><td>30</td><td>270</td></tr>
<tr><td>FeCrC+Ti</td><td>7</td><td>32</td><td>270</td></tr>
<tr><td>ER1</td><td>4</td><td>-</td><td>15</td><td>40</td><td>6</td><td>-</td><td>170</td></tr>
</table>

Where: I_{des} = Current desired; P = distance between center of adjacent weld beads; D = electrode diameter.

The welding parameters (Table 2) were obtained from Lima and Ferraresi (2006). The contact tip workpiece distance (DBCP) was varied to obtain the same welding current with the same reference voltage, as shown in Table 2. This procedure is important to evaluate the wear resistance of the weld deposit when using the same current and the same volume of metal deposited per length of bead (Valim and Vsold constant). For the covered electrode process the welding parameters were the same as used in industry and as indicated by the electrode manufacturer.

Figure 1 shows the top view of a hardfaced test plate as well as the transversal section where the test specimen was obtained. The wear tests used a Rubber Wheel Abrasion Tester, recommended for simulation of low-stress abrasion wear by ASTM G65 (1991) standard. Specimen 10 x 25 x 55 mm, disk 12.7 x 228 mm, rubber 60 shore A hardness, Brazilian standard n^{o} 100 sand (0.15 mm), wheel speed 200 rpm, test duration 10 min (procedure B), and force against specimen 130 N were used in tests. The specimens were weighed before and after the test with an electronic balance of resolution 10^{-5} g. Specimens were pre-worn during 5 minutes. Five tests were obtained for each type of wire.

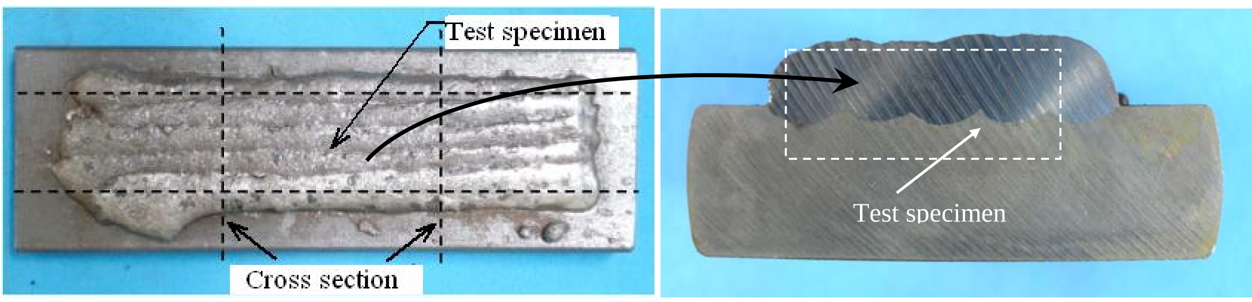
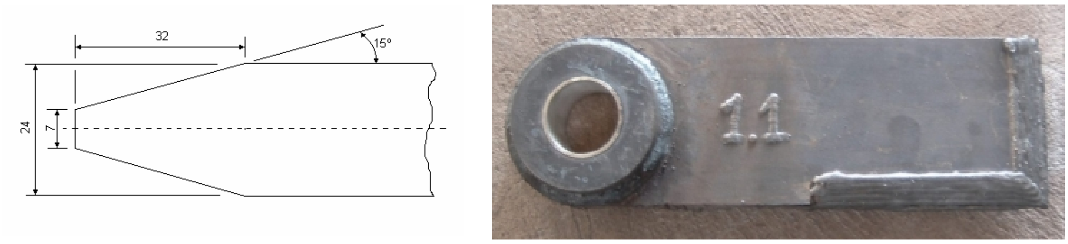


Figure 1.Test plate and region of the test specimen for wear and microstructure evaluation.

For the field tests (industry) twelve knives of 24 x 180 x 580mm of SAE 1020 steel were hardfaced using the welding parameters of Table 2. The steel sheets were cut as shown in Fig. 2 to obtain the region to be hardfaced (region which enters in contact with the sugarcane during shredding). Figure 2b shows a knife after hardfacing ready to be mounted in the shredder (each knife was hardfaced with twelve weld beads).



(a) (b)

Figure 2. Views of a shredder knife. (a) profile and dimensions (mm) of the bevel; (b) Photograph of a knife.

The 12 knife studied (each of the four consumables were used to hardface three knives) were mounted together with other 48 common knives. The knives mounted on the shredder were numbered according to the type of consumable and its position on the shredder. The knives were distributed between the 6 axles of the shredder (10 knives on each axle) as shown in Fig. 3.

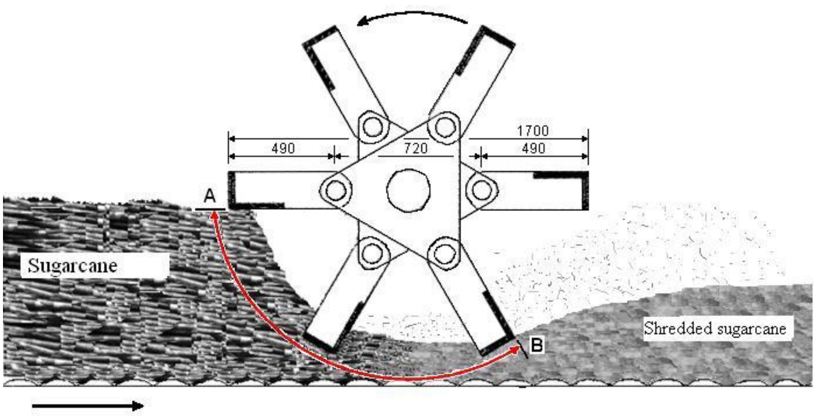


Figure 3. Schematic of shredder showing the contact of the knives with the sugarcane (unit mm).

Evaluation of the wear of the knives was by weight loss of the knives comparing the weight before and after the work period. The wear resistance was obtained in function of the distance travelled by the knife during field service.
The distance travelled by the knife while in contact with the sugarcane is difficult to define. It was verified that the height of the sugarcane on the conveyer belt is about 900 mm, which is about the height of the axle of the shredder. It was concluded that the contact between the knives and the sugarcane corresponds to about one third of the perimeter of the shredder (1.780 mm) as shown in Fig. 3. The arc AB represents the extent of contact between the knives and the sugarcane.

3. RESULTS AND DISCUSSIONS

3.1. Wear Resistance in Rubber Wheel Tests

Figure 4 shows the test results in terms of average wear resistance ($Rdesg_m$) for each consumable. Among the selfshielded flux cored wires, the best result was the +Nb wire, followed by the +Ti wire and the worst was the FeCrC wire. Although the lest two were statistically equal (Hypothesis Test). The covered electrode (ER1) was the second best result in general with an average mass loss of 26% greater than the +Nb wire. However by superposition of standard deviation the results are similar.

The superiority of the +Nb hardfacing compared the FeCrC hardfacing differs from the results of Buchely et al (2005) which evaluates hardfacings deposited by covered electrode process. According to which the first layer rich in chromium alloy presented greater low stress abrasion wear resistance than the alloy rich in complex carbides, such as NbC, M7C3 e Mo2C. Buchely et al. (2005) concluded that the hardfacings formed by complex carbides (C-Cr-W-Nb-Mo-V alloy) are inferior to the chromium carbides in the low stress abrasion test (Rubber Wheel) for both first and second layers.

For comparison in the results of Buchely et al. (2005) the wear resistance of his hardfacing varied from 11.2 to 32.3$(mg.m^{-1})^{-1}$, in one layer varied from 11.2 to 24.2$(mg.m^{-1})^{-1}$. In this study, the wear resistance of the single layer hardfacing varied from 7.67 to 34.4$(mg.m^{-1})^{-1}$.

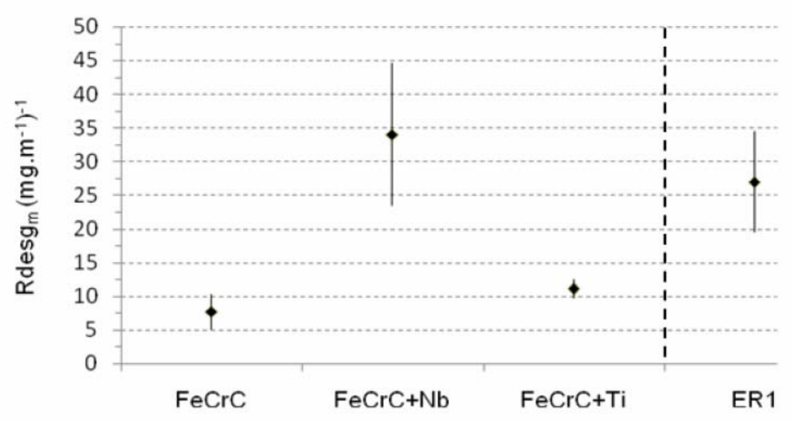


Figure 4. Analysis comparative of wear resistance.

A comparison between Buchely et al. (2005) and the hardfacing deposited by covered electrode process of this study are necessary in spite of welding conditions and electrodes being different. While the electrode of Fe-35Cr-4.3C de Buchely et al. (2005)presented wear resistance of the first layer of 14.7(mg.m^{-1})$^{-1}$, the ER1 electrode (Fe-44Cr-5.1C) of this study presented wear resistance much superior of 27.03(mg.m^{-1})$^{-1}$, indicating the importance of higher percentage of chromium and carbon to increase the low stress abrasion wear resistance.

The previous comparison showed that in spite of different consumables and different welding parameters, proportionally the results presented in this study are in agreement with literature.

The worn surfaces observed by optical microscope with amplification 50x for a more detailed analysis is shown in Fig. 5. Micro cuts predominated for all hardfacings with all consumables. For FeCrC and ER1 wires, the furrows caused by penetration of abrasive particles were deeper. The surface with +Ti hardfacing differently from the others showed a combination of phases with different behaviors of wear resistance. The regions more susceptible to the action of abrasive particles formed craters, scratches are observed both in peaks and in valleys. The FeCrC and +Nb wires resulted in hardfacings with cracks perpendicular to the weld bead. The +Ti hardfacing showed no visible cracks while the ER1 hardfacing showed cracks without preferential direction.

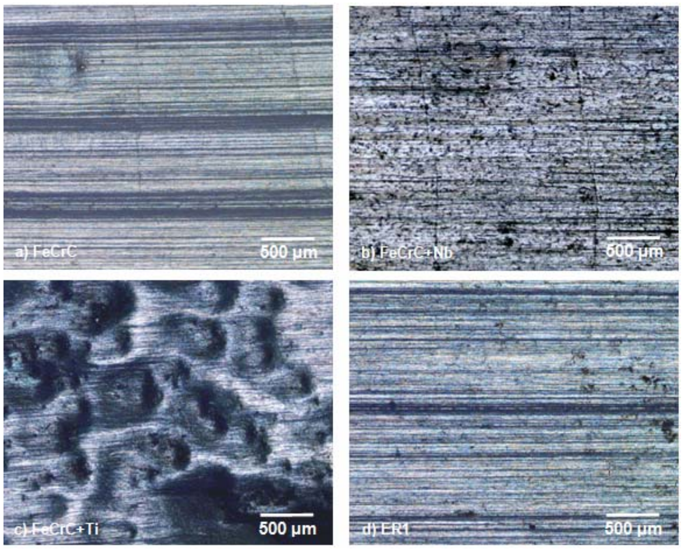


Figure 5. Optical microscopy image of the wear track.

3.2. **Field Performance Evaluation**

After twenty five days and milling of 132.000 tons of sugarcane, the field-test knives (Fig.2b) were dismantled and cleaned carefully to remove sugarcane residue, abrasive material and other foreign materials. In following were weighed to obtain the final mass and hence determine the loss of material. Fig. 6 shows one worn knife of each consumable with a detail of the region of greatest wear (the corner between the frontal edge and the superior edge). This region (the corner) passes closest to the conveyer belt and hence is the most demanded since the speed of the conveyer belt is less than the periphery speed of the knives. In the regions further from the corner, of both the frontal edge and the superior edge, the wear is less.

Figure 6 shows besides the wear by abrasion in all knives, a loss of metal by spalling of the harfacing principally those hardfaced with FeCrC and +Nb. Besides some los of base metal at the faces of the knives at the contact region with the sugarcane (polished surface of the knives in Fig. 6) and also loss of fragments of hardfacing at the start of the weld was found.

As the loss of mass is determined by weighing the knives it was not possible to separate the metal loss by abrasion and the loss by spalling of the hardfacing which in some cases is more significant. Fig. 7 shows the average weight loss ($Desg_m$) for each type of consumable. Among the selfshielded flux cored wires, the best result was obtained with the +Ti hardfacing, followed by the FeCrC hardfacing and the +Nb hardfacing had the greatest wear. The ER1 electrode presented wear similar to the +Ti hardfacing.

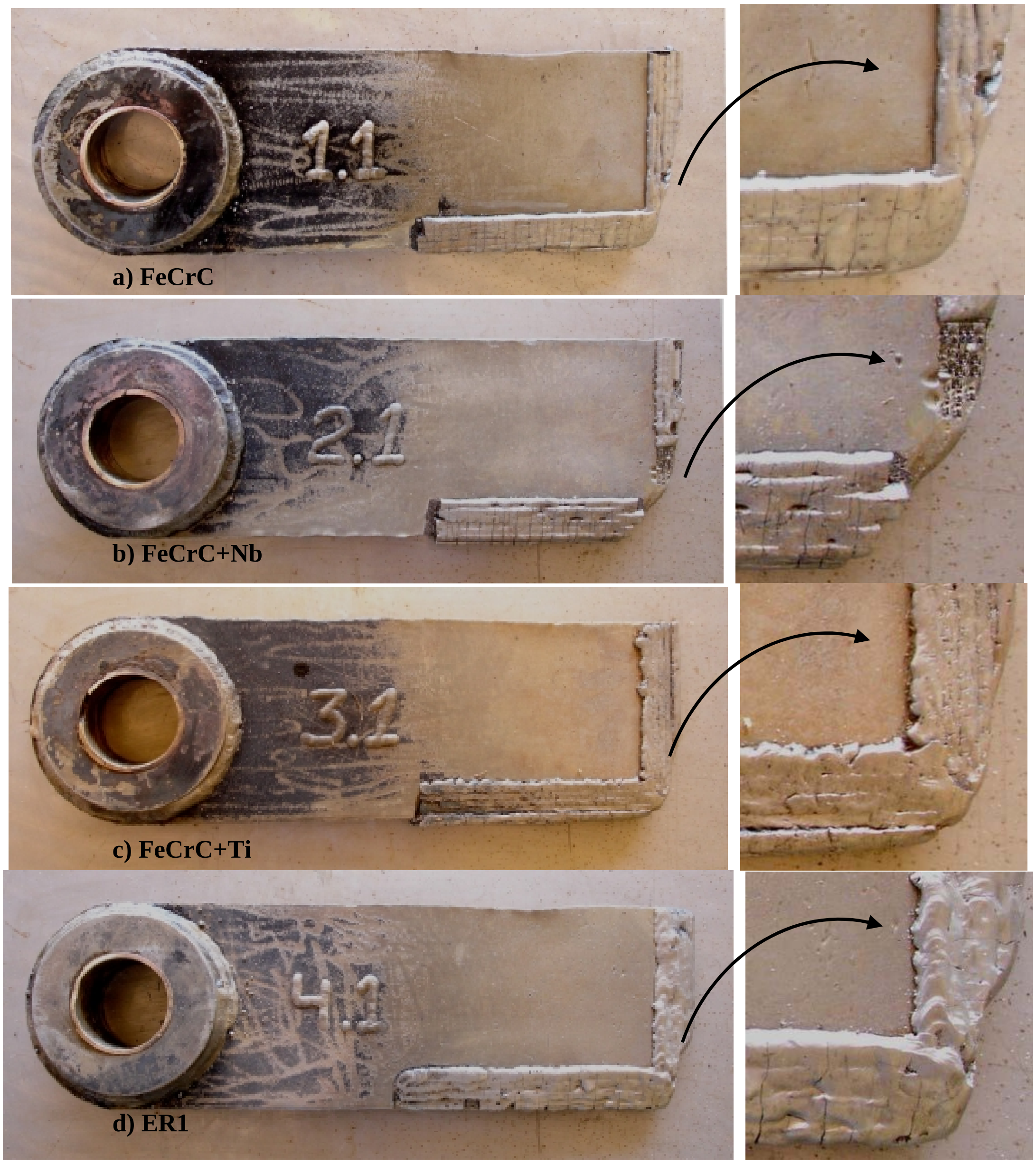


Figure 6. Worn knives, with detail of corner of greatest wear: FeCrC, +Nb, +Ti wires and ER1.

The greater wear of the +Nb hardfacing is due to fracture and spalling of part of the hardfacing, principally at the most demanded region. Since once the wear passes the hardfacing and reaches the base metal the rate of wear will increase. Thus the volume loss of the knife will accelerate.

A probable cause of spalling of the brittle hardfacings in region of many cracks can also be related with the impact of the knife against the structure of the shredder. These impacts happen during starting and stopping of the equipment and during shock of the knives with the sugarcane and any material in operation. The shocks at the region opposite to the attack edge, together with the impact with the sugarcane and other foreign materials at the frontal region (region of the attack edge) can be responsible for the growth and appearance of cracks and consequently for spalling of the hardafacing.

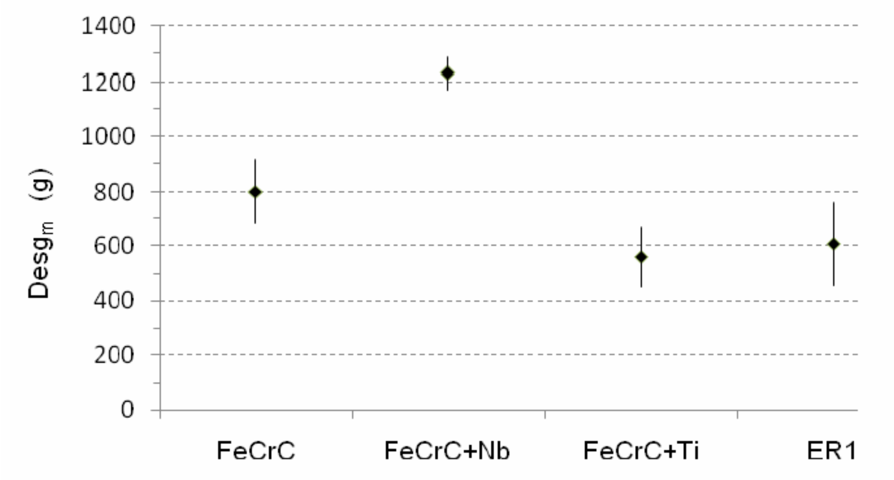


Figure 7. Average wear of the knives in field test.

Considering detachment of the hardfacing, it was suspected that the welding conditions used were not the best for FeCrC and +Nb wires. From the point of view of tensions generated during welding, the parallel beads favored the propagation of cracks and hence spalling of the hardfacing. As the wires presented different chemical composition, welding in the same conditions may not be their optimum. An investigation would be important to identify the optimum condition for each consumable in terms of crack control but preserving low dilution and high productivity.

According to Carceller (2007) the addition of manganese to the hardfacing alloys increases the impact resistance. In spite of the low percentage of manganese in the alloys weld, the hardfacing more affected by spalling were those with less manganese (+Nb and FeCrC wires). The third most affected by spalling, the ER1 electrode, had the third greatest percentage of manganese.

The average values of wear resistance of the knives hardfaced with the four consumables are shown in Fig. 8. The +Ti and FeCrC wires presented better wear resistence than the +Nb wire. The ER! Electrode presented average wear resistence ($Rdesg_m$) superior to the FeCrC and +Nb wires and slightly inferior to the +Ti wire, which was the best.

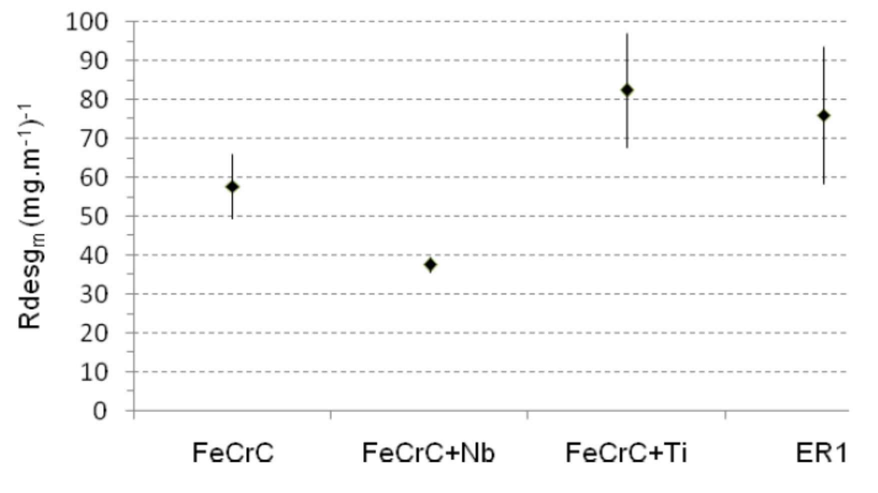
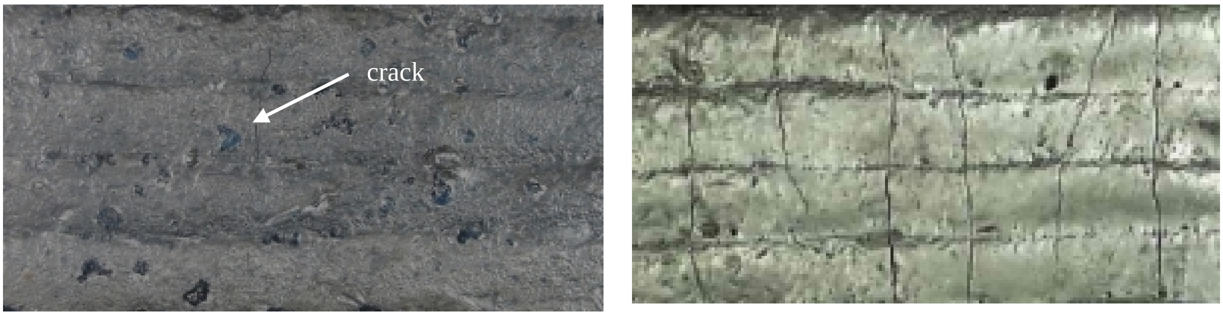


Figure 8. Average wear resistance for each consumable

The better wear resistance of the +Ti wire agrees with Gregory (1980) according to which the addition of Mo (present in the +Ti wire) in the hardfacing increases the abrasion resistance. Besides which, according to Wang et al. (2004), TiC is harder and more stable than CrC making materials reinforced with TiC to have stronger chains and better wear resistance.

The bad results of the +Nb wire is related to spalling of the hardfacing due to cracks and impact with the sugarcane and the shredder structure. In contrast to the good results of the +Ti wire which did not present visible cracks to the naked eye before and after use.

Figure 9 shows details of the same surface of a knife hardfaced with FeCrC wire before and after use. It can be verified visually that the size and number of cracks of the hardfacing created during welding (Fig. 9a), increased with use (Fig. 9b).



(a) (b)

Figure 9. Details of hardfaced knife surface: (a) before and (b) after use.

The cracks transversal to the weld bead are according to Wainer et al. (1991), contraction cracks due to low ductility or some times yield point of the hardfacing. The crack relieves the welding tensions. They are visible to the naked eye and grow with mechanical action.

Figure 10 shows details of the hardfacing with the four consumables at the attack edge close to the corner of greatest wear. The number of cracks of the FeCrC and +Nb wires are outstanding, provoking for the +Nb wire a marked fragmentation of the hardfacing in certain regions. In regions hardfaced with the ER1 electrode, besides cracks, removal of fragments of hardfacing was observed. While the hardfacing with +Ti wire was practically intact. In the detail of Fig. 10b there was no evidence of binding problem of the consumable but the fragmentation of the hardfacing due to cracks was clear.

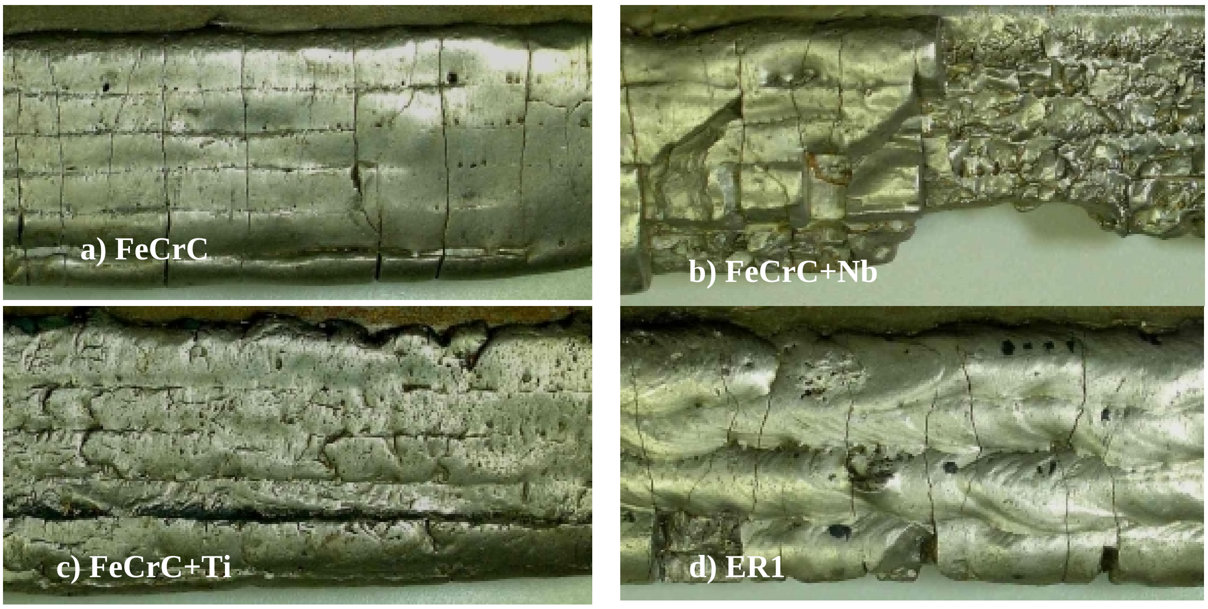


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Figure 10 – Details of the knives after use.

According Scotti and Rosa (1997) during welding cracks can appear due to the fragility of the hardfacing. These cracks are not necessarily indicators of reduction of wear resistance, and can be favorable by reducing the internal tensions. They are undesired in water-light hardfacings or when subjected to fatigue and hence removal of the hardfacing. However Martins Filho (1995) mentioned that for hardfacings of FeCrC alloy applied with flux cored wires, the absence of cracks is decisive for the increase of abrasive wear resistance.

Corrêa et al. (2006) declare that the FeCrC alloys are susceptible to cracks on solidification, which relief the weld tensions but in applications where the component is subjected to vibration or impact can lead to spalling of thr hardfacing. Hence the unceasing search to obtain alloys that present good wear resistance and tenacity.

It is believed that welding in conditions that minimizes the generation of cracks or obstruct their propagation can improve the performance of the two wires most affected by spalling, in agreement with the conclusion of Martins Filho (1995). Therefore it is suggested that future studies seek optimization of techniques and welding parameters, such as torch oscillation, attack angle, current, voltage, welding speed and nozzle contact-workpiece distance, besides metallic transfer mode and weld dilution to minimize crack generation. Scotti and Rosa (1997) showed in their study with flux cored wire of Fe-0.5C-5B alloy that it is possible to produce crack-free hardfacing deposits combined with high hardness by preheating and torch oscillation.

Figure 11 shows the profiles of the worn surfaces of the hardfacing applied to the shredder knives obtained by scanning electron microscopy. The scan of the surface of the test specimen at the region most affected by wear searches for similarity in profile or mechanisms.

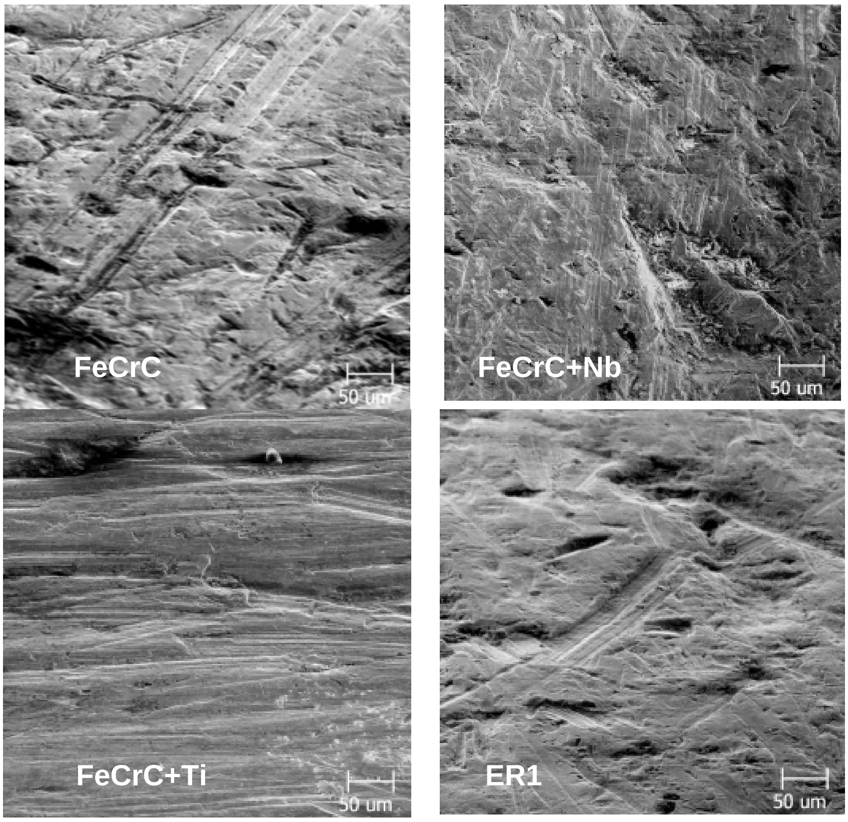

Figure 11. Profile of worn knife surfaces (amplification 200X).

In spite of the preponderance of micro cuts and cavities the surfaces of the different hardfacings were also distinct as shown in Fig. 11. The presence of craters in the FeCrC, +Nb and ER1 hardfacings indicated the removal of particles, probably carbides.

3.3. Wear in Laboratory Versus Wear in Field Test.

The relation between the wear resistance in laboratory and in field test were also different for the four consumable, indicating the different effect of the hardfacing properties of each consumable to resist abrasion in the different tribological systems.

Figure 12 compares the wear resistance in laboratory with that obtained in field test where the tools operated in real working conditions. Firstly the wear resistance of the hardfacings in laboratory (Rubber Wheel) was inferior to that of the field tests, indicating the greater severity of the former. This can be explained by the great severity of the laboratory conditions which guarantees always new abrasive with standardized size, besides constant pressure and feed rate at the rubber disk-test specimen interface. On the other hand, the eventual presence of bits of stone, iron and others foreign materials during the operation of the shredder tools as related by Buchanam, Shipway and MacCarney (2007), are supposed to be the exception in an efficient washing of the sugarcane and that the major cause of abrasive wear is the sugarcane (stalk, bark, knot, husks, etc) of lesser abrasion, besides remains of earth and sand of the washing process.

Figure 12 shows that the FeCrC and +Ti wires have similar behavior. The +Nb wire had the highest wear resistance (Rdesg) in the laboratory and the lowest wear resistance in the field test. The +Nb wire due excessive spalling presented excessive loss of metal in the field test. As discussed previously, the good performance of the +Nb wire in laboratory is due to its high resistance to abrasion while its poor performance in the field is related to the large number of cracks in the hardfacing.

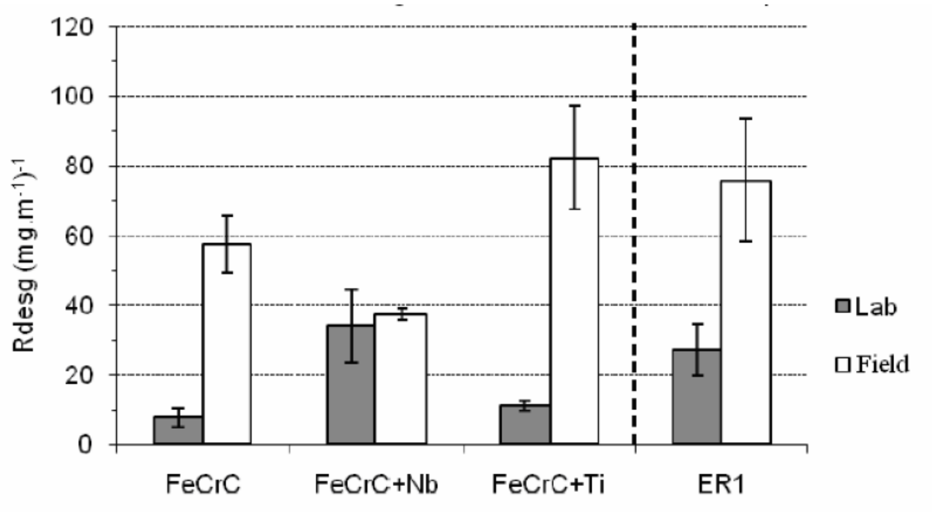

Figure 12. Comparison of wear resistance in laboratory versus field test.

The shielded electrode ER1 in comparison with the flux cored wires, showed a wear resistance in laboratory similar to the +Nb wire and a wear resistance in the field test similar to the FeCrC and +Ti wires.

The divergence between the laboratory and the field results is in agreement with Eyre (1991) according to whom it is difficult of preview with only one test the behavior in service of a material given the multiplicity of factors which intervene in the wear process. Thus it is not easy to find a test method appropriate for each tribological system.

The difference between the results of the laboratory and field tests indicate that the Rubber Wheel Abrasion Tests did not simulate accurately the wear observed with the sugarcane shredder knives in real working conditions. It is possible that the lesser presence of cracks of the +Ti hardfacing is the differential for its better field performance with impact with the shredder structure, the sugarcane and other foreign materials. It is believed that a test method that combines abrasion and impact will represent better the wear mechanism of the implements during operation. Since it is not always possible to evaluate the resistance of the hardfacings in true working conditions and when possible it is difficult and costly. It is believed that the identification of a representative test method will be important for future evaluations.

4. CONCLUSIONS

An analysis of the Rubber Wheel Abrasion Test led to the following conclusions:

- The worn surfaces showed predominance of micro cuts for all hardfacings. For FeCrC wire the predominance of micro cuts with deeper furrows were more evident. In the +Nb hardfacings micro cuts and micro furrows were observed. In the +Ti hardfacing a selective wear, that is, regions with marked different wear resistance, was observed.
- The +Nb alloy presented better low-stress abrasive wear resistance for single layer then the +Ti and FeCrc alloys.

An analysis of the field tests results (true working conditions) allows the following conclusions:

- The best wear resistance in field tests was obtained by shredder knives hardfaced with +Ti wire, followed by FeCrC and +Nb. Only the +Ti hardfacing presented performance superior to the ER1 electrode;
- The spalling of the hardfacing is decisive for the bad performance of the +Nb hardfacing and partially for the FeCrC hardfacing due to the formation and propagation of solidification cracks;
- The presence of discontinuities such as cracks and porosity can favor spalling of parts of the hardfacing, increasing the rate of wear in field conditions.
- The absence of cracks of the +Ti hardfacing is the differential for its better field performance in the presence of impacts with the shredder structure and other foreign materials. In opposite, the greater quantity of cracks of the +Nb hardfacing could be responsible for its greater mass loss.

The comparation between laboratory and field tests permit the following conclusions:

- From the abrasion point of view the field test is less severe than inl aboratory, where the best flux cored wire was five times more resistant than the worst flux cored wire;
- The best field performance of the sugarcane shredder knives is obtained with hardfacings that combine better resistance to abrasion with absence or lesser quantity of cracks;
- The rubber wheel abrasion test did not reproduce accurately the tribological system of the sugarcane shredder knives in true working conditions, since the incidence of impacts was not simulated.

5 ACKNOWLEDGEMENTS

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