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Waste-based consumable for hardfacing by welding: a look from the Circular Economy

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Abstract
In the present work, the obtaining of a consumable for the restore parts by welding from the perspective of the circular economy is addressed, using industrial solid residuals (slag from steel production, graphite from fragments of electrodes of arc furnaces) and agroindustrial residuals (ash from the combustion of biomass (rice husk)) and conceiving the non-generation of new solid residuals in the hardfacing process. The conceptual scheme of obtaining a sustainable consumable for hardfacing by Submerged Arc Welding (SAW) is proposed, establishing the internal symbiosis between the obtaining and application processes, as well as the symbiosis of these with external processes and the possibility of introduction to industrial practice. The obtaining of a flux based on residuals and its application in the hardfacing of pieces are experimentally validated, confirming the possibility of recycling the resulting slag.

Keywords: steel slag; rice husk ash; SAW fluxes; hardfacing by welding; circular economy.

Consumible basado en residuales para recargue por soldadura: una mirada desde la Economía Circular

Resumen
En el presente trabajo, se aborda la obtención de un consumible para la recuperación de piezas por soldadura desde la perspectiva de la economía circular, empleando residuales sólidos industriales (Escorias de la producción de acero, grafito de fragmentos de electrodos de hornos de arco) y agroindustriales (cenizas de la combustión de biomasa (de cascarilla del arroz)) y concibiendo la no generación de nuevos residuales sólidos en el proceso de recargue. Se propone el esquema conceptual de la obtención sustentable de un consumible para el recargue por Soldadura por Arco Sumergido (SAW, por sus siglas en inglés), estableciéndose la simbiosis interna entre los procesos de obtención y aplicación; así como, la simbiosis de estos con procesos externos y la posibilidad de introducción a la práctica industrial. Se valida experimentalmente la obtención de un fundente a base de residuales y su aplicación en el recargue de piezas, confirmándose la posibilidad del reciclado de la escoria resultante.

Palabras clave: escorias de acería; cenizas de cascarilla del arroz; fundentes SAW; recargue duro por soldadura; economía circular.

1 Introduction

The production of consumables for hardfacing by SAW, to restoring parts or manufacturing new cheaper or more durable parts, is carried out fundamentally based on natural minerals, implicitly carry an environmental cost due to the deterioration of ecosystems caused by mining activity [1]. However, the use of solid waste is reported in obtaining new consumables for welding surfacing [2-8], and even the AWS A 5.17 standard [9] declares the reuse of slags in SAW joint welding of carbon steels.

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Surfacing to restore worn parts and return them to service, extending their useful life, or to manufacture new highly durable parts, implies a sustainable approach. This becomes even more evident if a consumable made from waste is used. However, to date, there is only one report on the application of the Circular Economy concept when addressing part hardfacing by SAW [8]. In this work, the non-generation of a new solid residual was not set as a goal (it was not planned to apply the slag resulting from welding overlay).

The Circular Economy is proposed as the logical and viable alternative, which corrects the main problems of linearity (production, use and disposal of goods) and aims for products, components and resources in general to maintain their usefulness and value at all times or which is the same, zero residues [10-13]. In this sense, several authors validate the conception of the Circular Economy, based on the 3R model (Reduce, Reuse, Recycle) or the 4R (Reduce, Reuse, Repair, Recycle), as sustainable solution in sectors with high consumption of natural mineral resources and that produce large volumes of solid waste [14-16].

Based on what has been discussed, the objective of this work is to obtain a consumable based on residuals to restore pieces by welding, from the Circular Economy perspective.

2 Materials y methods

2.1 Scheme for obtaining and applying a consumable for hardfacing parts by welding from the circular economy perspective

Fig. 1 shows the conceptual scheme of sustainable obtaining and application of a consumable for the restore of parts by SAW, from the Circular Economy perspective. The scheme considers the symbiosis of two processes, obtaining a flux (a) and parts hardfacing (b). It also considers symbiosis with external processes, while conceiving the non-generation of a new residual.

2.2 Obtaining the consumable

According to the diagram in Fig. 1 (Process framed by (a)), a flux was obtained to hardfacing parts subjected to abrasion. The composition of the flux matrix was established in a previous study (72.99 % slag from steel refining in the ACINOX Las Tunas ladle furnace, 20.44 % ash from the combustion of rice husk and 6.57 % of fluorite) [5]. In the present work it was decided to prepare the mixture of the flux matrix without flourite, since the slag from the fusion of said matrix, even without CaF_2, satisfies the requirements, having a location in the pseudowallastonite region of the system CaO-SiO_2-MgO, with melting temperatures around 1400 ºC [5,7]. The non-addition of fluorite favorably leads to a decrease in the flux/wire consumption ratio in hardfacing. In this way, the composition of the flux matrix to be produced is as follows: 78.12 % slag from steel refining in a ladle furnace and 21.88 % ash of rice husks.

According to previous results [6,7], the flux is composed of 83 % matrix and an alloy system (7% graphite and 10 % FeCrMn). The total dry mass to obtain the flux is composed

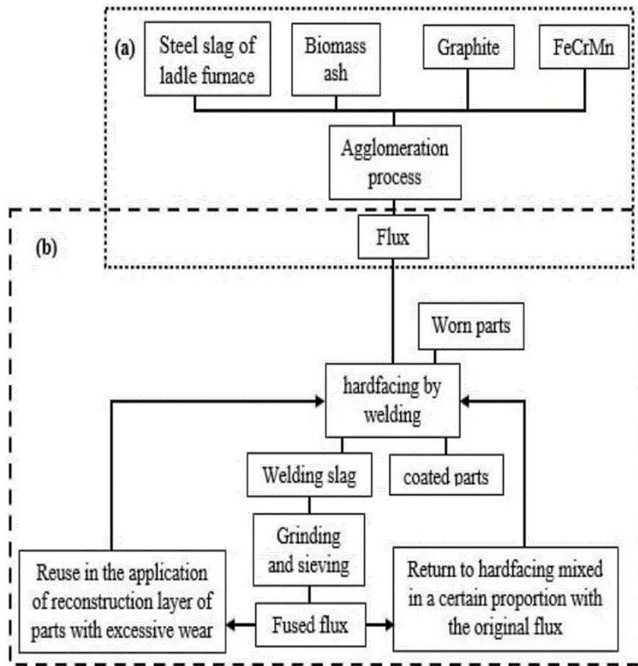

Figure 1. Scheme for obtaining and sustainable application of a consumable for parts hasrfacing by welding from the Circular Economy perspective.
Source: Own elaboration

of: 64.84 % ladle furnace slag, 18.16 % rice husk ash, 7 % graphite and 10 % FeCrMn. Compositions of raw materials; as well as the procedures followed for its preparation and for obtaining the flux were previously reported [7].

The matrix components were sieved to a grain size less than 0.25 mm (steel refining slag and rice husk ash are fine granulated materials, that do not require grinding for use in welding consumables [5,7]); while FeCrMn and graphite were ground and sieved in a range between 0.1 mm and 0.25 mm. To obtain the flux, a mixture of 1 kg of dry mass was prepared. The components were mixed for 30 min in a rotating drum with an inclination of 5°, to ensure the homogeneity of the mixture. The components to the drum were added in increasing order of their densities, to facilitate counterflow mixing.

The flux was manufactured by pelletization, using sodium silicate as a binder, in a proportion of 30 % in relation to the dry mass. The flux was air dried for 24 h, then it was sieved to a particle size between 0.25 mm and 2.5 mm and finally it was calcined in a muffle furnace for 120 min at 350 °C.

2.3 Obtaining and characterization of weld deposits

With the flux, using a Mansfeld Submerged Arc Welding machine at the UCLV Welding Research Center (CIS), a bead-on-plate deposit was obtained. As in previous works [7], a 150x80x8 mm AISI 1020 steel plate was used as the base metal. The 3 mm EL12 electrode wire was used, using a current of 400 A, with normal polarity. The welding speed was 30 m/h, the arc voltage was 30 V. To guarantee cooling conditions, similar to the hardfacing of real parts, and to avoid deformations of the sheet, it was fixed on a device to perform the deposition. (Fig. 2).

Figure 2. Deposition on fixed plate to achieve heat extraction and prevent deformation
Source: Own elaboration

Two overlapping beads were deposited, positioning the electrode above the edge of the first bead to make the second, in such a way that a sufficient area was covered for the subsequent extraction of the specimens and the dilution with the base metal was attenuated.

From the deposit, the samples were extracted by means of transverse cuts on a metallographic cutting machine, for determination of chemical composition by Optical Emission Spectral Analysis and another for metallographic characterization and determination of hardness. The chemical analysis sample was roughed off at the top of the deposit, by grinding, to achieve a sufficient area for the incidence of the arc in the analysis. The metallographic sample was prepared in the cross-sectional part of the deposit. The sample was grinded and polished, in accordance with the ASTM E3 standard [17]. The attack was carried out by immersion with 2 % nital reagent, according to the ASTM E407 standard [18]. Fig. 3 shows the macrograph of the deposit, captured with a low magnification microscope.

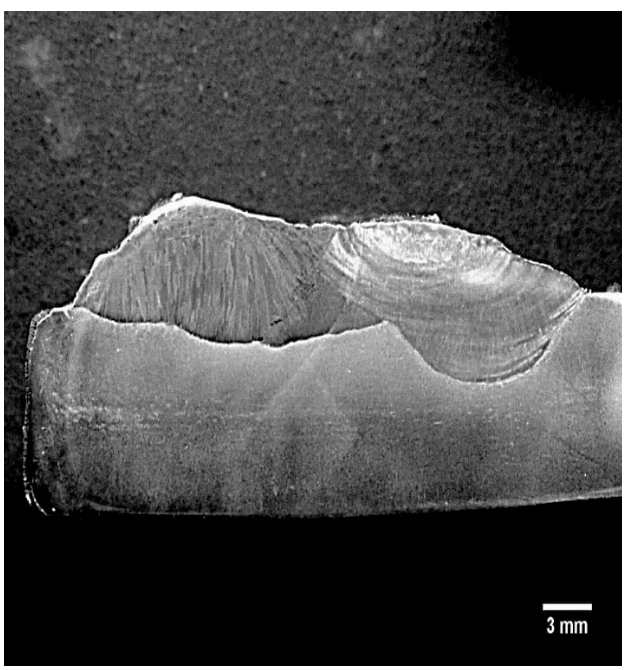

Figure 3. Macrograph of the deposit.
Source: Own elaboration

The metallographic observation was carried out by optical microscopy, in the upper center area of the second deposited bead (right bead in Fig. 3). In that same region, the Vickers hardness was measured with a microhardness tester, using a load of 1000 g and an indentation time of 10 s.

3 Results and discussion

3.1 Analysis of the circular economy perspective in obtaining a consumable for hard facing using residuals

Obtaining the consumable (Process (a) in Fig. 1) is based on the use of three residuals, slag from steel refining in a ladle furnace, graphite from electrode fragments from the steelmaking furnace, and ashes from the combustion of biomass (In this work, rice husk ash was used). This process of obtaining the flux (Process (a) in Fig. 1) has external symbiosis with the process of obtaining steel, because ladle furnace slag and graphite from fragments of electrodes are used. Has external symbiosis too with agroindustry through the use of ashes from the combustion of biomass and with the production of FeCrMn by aluminothermy [19].

Internally, obtaining the consumable (Process (a) in Fig. 1) has symbiosis with the parts hardfacing process (Process (b) in Fig. 1). In Process (b) in Fig. 1, internal symbiosis is carried out by recycling the slag in the same parts hardfacing process.

Externally, the hardfacing process (Process (b) in Fig. 1) has symbiosis with the repair and maintenance processes of equipment and facilities, since it returns worn parts to service or manufactures parts on a cheaper substrate.

According to what was discussed, in the scheme of Fig. 1, the conception of the Circular Economy is validated [10-16], since a marked emphasis is placed on the use of residuals and the non-generation of new residuals; as well as, because worn parts are returned to service (the useful life is extended). That is, residuals are reduced (slag from steel production and biomass ash), graphite is reused, worn parts are restored and the slag generated in the hardfacing is recycled. Additionally, the matrix components (steel refining slag and rice husk ash) do not require grinding, which means energy savings compared to the use of natural minerals in the flux matrix.

If the symbiosis of processes in Fig. 1 is integrated into the analysis of the possibility of obtaining and applying the consumable in industrial practice, four possibilities are noted:

1. Produce the hardfacing consumable (Flux for SAW) (Process (a) in Fig. 1) in a metal-mechanical company

whose object is the hardfacing of parts (Process (b) in Fig. 1).

2. Produce the hardfaciong consumable (Process (a) in Fig. 1) in a company that has infrastructure for the processing of granular materials and the production of agglomerates (company that produce clay elements, for example). This would supply the consumable to companies that perform hardfacing of parts by welding (Process (b) in Fig. 1).
3. Produce the hardfacing consumable (Process (a) in Fig. 1) in the steel producing company, where the slag, that constitutes the majority raw material to produce said consumable, is generated. The steel company would supply the manufactured consumable to metalworking companies that perform hardfacing of parts by welding (Process (b) in Fig. 1).
4. Produce the consumable (Process (a) in Fig. 1) in the steel producing company, where the slag is generated. Unlike the previous variant, this entity would also perform the parts hardfacing process (Process (b) in Fig. 1) for itself and for other companies.

Variants 2 and 3 consider producing the consumable (Process (a) in Fig. 1) in one company and performing the hardfacing in another (Process (b) in Fig. 1). There are the least viable, since recycling the slag from the hardfacing would be more difficult. In this case, the user of the consumable must also have equipment for crushing and sieving the slag from the hardfacing. In this sense, variant 1 is more viable than the previous ones, but requires that the company dedicated to the processes of manufacturing and restoring parts (Process (b) in Fig. 1) diversify, integrating operations of crushing, grinding, sieving, agglomeration, etc., to manufacture the consumable (Process (a) in Fig. 1).

Variant 4 is considered the most comprehensive solution, since the fundamental raw material for the manufacture of the consumable (Process (a) in Fig. 1) is the slag from steel refining in a ladle furnace. The steel production industry itself generates graphite electrode fragments as waste, this being another component to manufacture the consumable (flux). In turn, the ashes from the combustion of rice husks are used in steel company as a thermal insulating coating powder for liquid steel. The volumes of ash to be consumed, to satisfy the demand for the hardfacing consumable, would be insignificant compared to the frequent consumption of this agroindustrial residual (ash) in steel production. On the other hand, FeCrMn is an alloy also developed from waste, with mill scale being used to obtain it [19]. Therefore, obtaining FeCrMn could be integrated with the production of the hardfacing consumable (flux), especially because it does not require specialized equipment and facilities, while at the same time it would give application to another waste product from steel production (the mill scale [14,15]). FeCrMn to obtain the consumable for hardfacing parts can be replaced by commercial FeCr and FeMn, which are frequently used in steel production.

Additionally, steel production is related to the manufacturing and use of hardfacing consumables. The steel mill has the infrastructure (available areas, connections, laboratory equipment for grinding, sieving, mixing, etc.), which are often underutilized and which have the appropriate dimensions for the production of the hardfacing consumable (flux). At the same time, the steel industry has mechanical workshops that allow parts to be restored, since maintenance and repairs are required within the company itself.

3.2 *Analysis of the deposited metal characterization*

Table 1 shows the chemical composition of the deposited metal. This is characterized by C, Cr and Mn contents typical of hardfacing deposits to abrasive wear, according to AWS A 5.13 [20]. The silicon content (Table 1) is much higher than what is provided of this element in the wire-flux system (is provided by the wire and FeCrMn). This is a result of the fact that, in the high temperature zone (in the drop and the front area of the weld pool), the endothermic oxidation reaction of the metal in the weld pool by the SiO_2 of the flux develops intensely (Eq. 1), while C and Mn act as deoxidizers (Eq. 2-3), releasing iron and favoring the silicon reduction reaction by eq. (1) [7].

$$2Fe + (SiO_2) \rightarrow [Si] + 2\,[FeO] \quad (1)$$

$$[Mn] + [FeO] \rightarrow (MnO) + Fe \quad (2)$$

$$[C] + [FeO] \rightarrow CO + Fe \quad (3)$$

According to the high cooling rates and the preferential orientation of heat extraction in the surfacing by arc welding; as well as, the chemical composition of the deposited metal (Table 1), the microstructure (Fig. 4) is characterized by a high predominance of martensite (with possible some presence of bainite) and with austenite in the interdendritic region. This microstructure is appropriate for low stress abrasion conditions [3,5-7,20]. After deposition, the liquid metal cools, undergoing a primary crystallization of austenite in dendritic form, which, under conditions of high cooling rates, undergoes the non-diffusive transformation to martensite in the solid state. In the primary crystallization process, there is a certain tendency for the alloying elements to segregate, without reaching equilibrium conditions due to the high cooling rates. Austenite remains in the interdendritic region, which crystallizes last and does not undergo transformation.

Table 1 shows the average hardness of the deposited metal. According to the hardness value (about 57 HRc), the predominance of martensite in the dark dendritic region is confirmed (Fig. 4) [3,5-7,20]. The elements C, Cr and Mn influence hardenability, since they favor the transformation from austenite to martensite by shifting the pearlitic transformation curves to the right. These elements reduce the starting temperature of the martensitic transformation, which leads to a certain presence of retained austenite [6,7]. Carbon is responsible for the tetragonality of martensite, which consequently influences the hardness.

Table 1.
Chemical composition (% mass) and Vickers hardness of the metal deposited with the experimental flux

C	Mn	Cr	Si	HV_{1000}
1,68	1,61	0,52	1,44	621,4

Source: Own elaboration

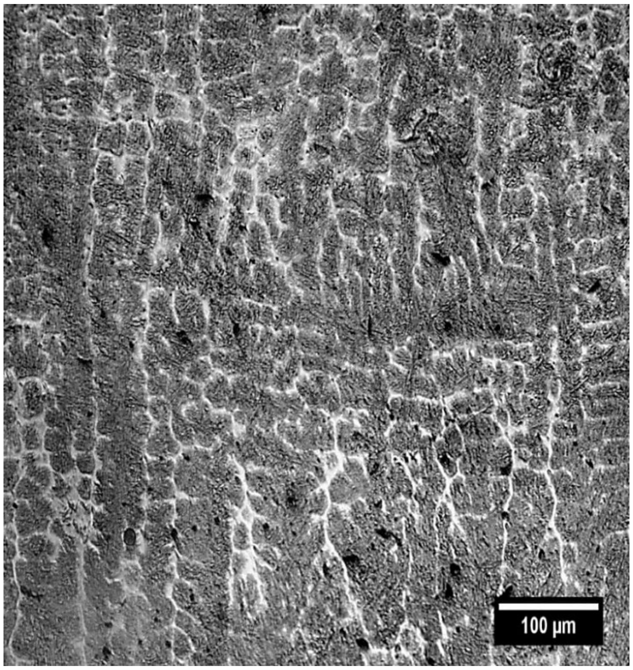

Figure 4. Microstructure of the deposited metal.
Source: Own elaboration

The AWS A 5.13 standard [20] reports the classification of EFe5 hardfacing deposits, whose composition is similar to the deposit obtained (Table 1). This standard declares that this EFe5 classification corresponds to a tool steel for cold work, with a hardness between 50 and 55 HRc, suitable for work with high compression stresses, moderate abrasion and metal-to-metal wear. Previous works [3,5-7] report, as suitable for abrasive wear, hardfacing deposits with composition and microstructure similar to those of the present (Tables 1 and 2, Fig. 4). Haiko et al. [21] even validate the adequate abrasive wear behavior of a lower hardness steel, with a predominance of bainite.

3.3 Analysis of slag formation in the hardfacing process to evaluate its recycling

As stated in section 2.2, the flux matrix is containing 78.12 % slag from steel refining in a ladle furnace and 21.88 % ash from the combustion of rice husks; while in the flux, the matrix represents 83 % and the rest corresponds to the alloy system (7% graphite and 10 % FeCrMn). Thus, the components of the dry mass of the flux represent 64.84 % slag from steel refining in a ladle furnace, 18.16 % rice husks ash, 7 % graphite and 10 % FeCrMn. When agglomerating with sodium silicate (the composition of sodium silicate is [7]: SiO_2- 29.39%; Na_2O- 10.10% and H_2O- 60.51%), at 30% in relation to the dry mass of 1 kg (648.4 g of ladle furnace slag, 181.6 g of rice husk ash, 70 g of graphite and 100 g of FeCrMn), this provided 88.2 g of SiO_2 and 30.3 g of Na_2O, since the water evaporated during the drying and calcination of the flux. Then the percentage ratio of the slag-forming flux components, considering the contribution of SiO_2 and Na_2O from the silicate is: 66.96 % of steel refining slag, 19.79 % of rice husk ash and (9.89 % SiO_2 + 3.39 Na_2O) provided by sodium silicate.

Based on the aforementioned percentage ratio of the slag-forming components in the flux and the compositions of the ladle furnace slag and rice husks ash, reported in a previous work [7], the composition of the slag, that is formed in the hardfacing with the experimental flux, was calculated (Table 2). It is observed that the formed slag is characterized by the majority CaO, SiO_2, MgO system, which represents 90.73 % of the total slag composition and, therefore, the ternary phase equilibrium system (Fig. 5) can be used to evaluated the phase composition and fusibility of the slag that is formed in the hardfacing with the flux [1,5,7,22].

The composition in Table 2, recalculated to 100 % of the CaO-SiO_2-MgO ternary system, corresponds to: 43.32% CaO, 50.53% SiO_2 and 6.15% MgO. Fig. 5 shows the location of this composition, showing that it´s localized in the pseudowalastonite region, around the melting temperature of 1400 °C. This location satisfices the basic flux behavior, melting before the electrode wire and the base metal, which have a fusion temperature around 1500 °C, thus guaranteeing the protection of the molten metal. Such localization in the pseudowallastonite zone (Fig. 5) coincides with the literature [1,2,5,7], which means a clear indication that it´s possible to recycle the slag in the same hardfacing process.

Table 2.
Composition of the slag that is formed in hardfacing with the experimental flux (% mass).

NiO	**Cr_2O_3**	**MnO**	**FeO**	**CaO**	**MgO**	**SiO_2**
0,06	0,03	0,64	0,77	39,30	5,58	45,85
Al_2O_3	**P_2O_5**	**SO_3**	**TiO_2**	**V_2O_5**	**Na_2O**	**K_2O**
3,50	0,02	0,56	0,20	0,02	3,46	0,01

Source: Own elaboration

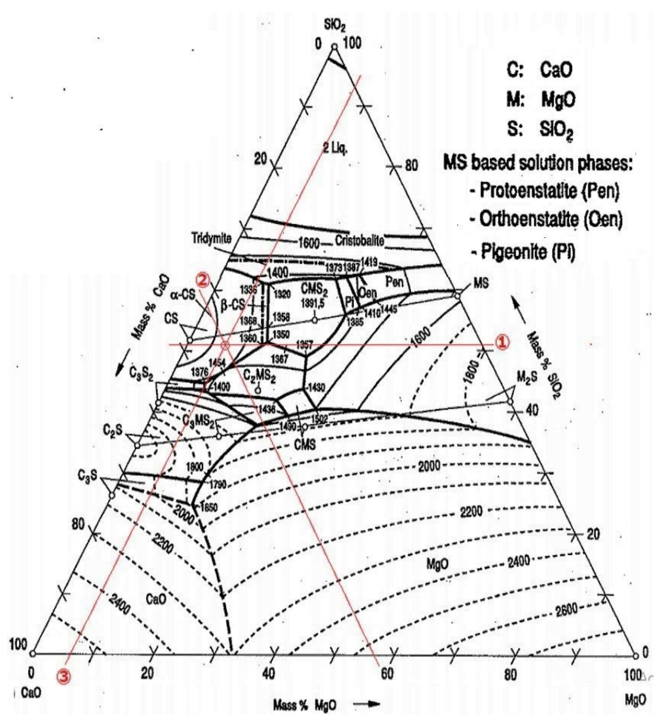

Figure 5. Ternary diagram of CaO-SiO_2-MgO phase equilibrium system. (The lines, identified with the numbers 1, 2 and 3 inside a circle, represent the contents of SiO_2, CaO and MgO and their intersection corresponds to the location of the composition)
Source: Allibert, 1995.

4 Conclusions

- The obtaining of a consumable (Flux) based on residuals for the parts hardfacing by welding is validated, from the Circular Economy perspective, conceiving the non-generation of new residual.
- The proposed scheme for sustainable obtaining and application of a hardfacing consumable (flux), shows the symbiosis between the processes of obtaining the consumable and parts hardfacing; as well as the external symbiosis of these with other processes such as obtaining steel and agribusiness.
- The most sustainable and comprehensive variant of introduction to industrial practice of the obtained consumable consists of: Obtaining the consumable in the steel producing company, where the slag, that is the majority raw material, is generated, and carrying out the parts hardfacing in the same company to satisfy internal demand and for others companies.
- The experimental consumable makes it possible to obtain a deposited metal, appropriate for parts working in abrasive wear. The deposited metal, corresponding to high carbon and low alloy steel, with a predominance of martensite in the microstructure and, consequently, which a high hardness (57 HRc).
- The slag from hardfacing with the experimental flux corresponds to the CaO-SiO_2-MgO ternary system, located in the pseudowallastonite region, being appropriate for recycling in the same hardfacing process.

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