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CORE WIRE FOR AUTOMATIC (MANLESS) ALLOYING OF IRON IN Al ALLOYS THROUGH THE CHARGE WELL OF ELECTROMAGNETIC PUMP

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Abstract

For the aluminium industry, considering the rapid and continuous melting procedures achieved in furnaces coupled with an electromagnetic pump (EMP), it would be advantageous to develop iron alloying additives with significantly higher dissolution rates and recovery level, as well as a fully automatic alloying procedure through the charge-well of the EMP.

The quality of alloying performed with cored wire was found to be at least equivalent to the quality achieved by commercial Al-Fe tablets and briquettes. On the other hand, the cored wire results in several important benefits, such as fully automatic and more accurate feeding regulation, lower alloying cost, significantly lower oxidation of molten aluminium as a result of alloying without the need to open the door of the melting furnace, higher yield of alloying additive and the complete dissolution of iron particles in the melt, which could not be achieved in such a short time by tablets and briquettes.

Key words: cored alloying wire, aluminium alloying, electromagnetic pump

Introduction

General considerations on dissolution of iron into the molten aluminium

Iron alloying is an important processing step in the production of AA 8xxx aluminium alloys, especially if these are applied in the production of highly demanding surface quality end-products (thin gauge aluminium foils, lithographic and high bright sheet, etc).

Various tabletted or briquetted iron additives for alloying aluminium have been in use for many years for manufacturing high-quality aluminium alloys in applications

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such as rolling ingot for foil-stock and can-stock, billet for precision extrusions and high-quality foundry casting alloys.

Current global trends in improving the melting rate and melting recovery of aluminium scrap and achieving a uniform distribution of alloying elements favour the development of advanced alloying additives with significantly higher dissolution rates and recovery level. Producers equipped with advanced melting devices (e.g. twin chamber melting furnace) coupled with an electromagnetic pump (EMP) for achieving a high melting rate and uniform distribution of alloying additives are particularly interested in fully automatic and manless alloying through the charge-well of the EMP. Currently, various forms of non-ferrous alloying additives (mostly silicon) are fed directly into an aluminium melt vortex created under the action of molten metal pumping. This additionally improves the quality of alloying, enhancing the wetting and solubility of the additives in molten aluminium. However, since ferrous alloying additives, of which iron is the most important for the aluminium industry, could be influenced by the alternating magnetic field of the EMP, their alloying through the charge-well of the EMP is technically more demanding. Actually, the non-proper performed alloying of iron could even cause the immediate blockage in the EMP system or could influence to the various levels the quality of the final product.

In order to make the automatic, manless and continuous alloying of iron through the charge-well of an EMP a routine operation, it is absolutely necessary to complete the dissolution of the iron particles in the molten aluminium before entrance into the return leg of EMP. Hence, the time for complete dissolution of iron particles in molten aluminium should be shorter or, in the worst case, equal to the time the iron particles need to circulate and be dispersed in the melt, from the charge-well of the EMP and through the return leg tube to the pump tube connected to the melting furnace.

In practice, the dissolution time is influenced by several parameters, among which the most important are powder morphology and chemical composition, temperature and chemical composition of the molten aluminium alloy, stirring conditions, etc.

In this article, a convenient cored alloying wire, similar in design with widely used for alloying of steel, is proposed for fully automatic and continuous alloying of molten aluminium with iron through the charge-well of the EMP.

Such cored wires are produced by numerous commercial manufactures, some of whom are also located in Slovenia.

The influence of the magnetic field on the dissolution of iron

In the conventional manufacturing way of iron-containing aluminium alloys, the addition of iron is currently practiced in various forms of iron scrap or lumps of an Al-Fe master alloy containing about 5-30 wt% of iron. Iron powder and iron-powder based tablets or briquettes are also used because of the advantages they offer in the form of shorter dissolution time.

Irrespective of the iron additives used for alloying in molten aluminium, iron exists in the form of intermetallic compounds of branch, lumpish and spherical shape. In addition, during rapid melting in twin chamber melting furnace, iron particles often do not dissolve completely in molten aluminium. This is particularly case if iron particles are surface oxidised or covered by an intermetallic layer precipitated from the melt in an early stage of reactive dissolution.

When various intermetallic inclusions or/and partly dissolved iron particles dispersed in molten aluminium enter in an alternating magnetic field of EMP, the change of magnetic flux induces the circulation of electric currents simultaneously in the molten aluminium and all dispersed particulates. The density of the current, J, induced by the change of magnetic flux can be written as [1]:

$$J = \sigma E = rotH \qquad (1)$$

where σ is the electrical conductivity, while vectors E and H represent electrical and magnetic field, respectively.

The direction of the inductive current is perpendicular to the direction of the applied magnetic field and electromagnetic force (Lorentz force) will be generated. The difference of electrical conductivity between dispersed particulates and the melt will result in different electromagnetic forces on them, creating the resultant aggregating force, under which various iron rich particulates will be orientated and some of them also aggregated in coarse inclusions. The aggregating force, F_p, can be expressed as [1]:

$$F_p = J_p \times B\, V_p - J_{Al} \times B\, V_p \qquad (2)$$

where V_p is the volume of iron-rich particulates, J_p and J_{Al} are the density of current on iron-rich particulates and molten aluminium, respectively and B is the magnetic flux density.

The only way to prevent such a influence of the alternate electromagnetic force on particulates dispersed in molten aluminium, is to achieve the complete dissolution of iron additives before entering inside the tube of EMP. Thereof, the time for complete melting of iron particles or additives in molten aluminium should be, at least, equal to the time they need to circulate, carried by the melt, from the charge-well of EMP to the pump tube in the main chamber of TFC furnace. Passing through the return leg tube of the charge-well, particles travel to the side well chamber of TFC, and then to the main chamber of TFC.

Based on an average pumping capacity of EMP (about 10 t/min) and the typical size range of industrial melting furnaces (20-80 t), one can calculate that the iron particles dissolving time should be about 2-8 min.

On the other side, the iron particles dissolving time in molten aluminium depends both on iron powder characteristics (morphology and chemical composition of iron particles) as well as the several parameters of the molten metal (temperature, chemical composition, stirring conditions, etc.).

However, the stirring of the melt inside the vortex will accelerate the flux of material dissolving from the surface of iron particles, theoretically by the square root of its angular velocity in the vortex [2].

The existing iron alloying techniques

The dissolution of iron particles in molten aluminium can be improved by applying fine powders (having no particles larger than 800 μm) and substantially free of oxides (typically with a total oxygen content below 0.09 wt. %).

One common way of introducing such fine and chemically pure powders into a melt is injection with an inert carrying gas through a lance. The powder is injected into the vortex in the charge-well of an EMP. The temperature of the aluminium melt is kept in the range 720-760 ºC, which is the normal alloying temperature irrespective of the alloying method applied. The stirring of the melt inside the vortex accelerates the flux of material dissolving from the surface of the iron particles, theoretically according to the square root of its angular velocity in the vortex [1].

However, iron powders suitable for injection are rather expensive and should be stored in a protective atmosphere, which additionally increases the cost of alloying. In addition, the injection of individual iron particles into molten aluminium could also result in a significant rejection of particulates, which decreases the alloying efficiency and also increases the cost. Moreover, the possibility of achieving a high alloying rate (mass of iron powder introduced into the melt during the alloying time) is also very important for industry. Typically, in industrial alloying, 80-150 kg of iron powder should be introduced into a melt over a period of time of about 30-45 minutes. Such high alloying rates, required in continuous casting lines, could be obtained by injection only with great alloying experience.

Another well-practiced way of alloying iron in the aluminium industry is by using a mixture of iron and aluminium powders pressed into various commercially available tablets and briquettes of different sizes and weights. The total amount of iron needed for alloying introduced into the melt by submerging individual tablets or briquettes is about 0.25 to 1 kg of iron particles bonded with 15-20% of aluminium powder. However, due to the great mass of iron in an individual tablet or briquette, this way of alloying creates a high local concentration of iron near the tablet, which could influence the microstructure of the solidified alloy. Possible oxidation of both iron and aluminium particles in tablets or briquettes, particularly in the case of their incorrect storage or during preheating on the ramp, could also occur.

The cored alloying wire design development

A convenient cored alloying wire is proposed for such an alloying, consisting of a porous iron powder core with 40% porosity and an aluminium cladding of 0,5mm thickness. Wire was produced by the traditional welding technique, using AA 8011 hot rolled Al strip from Impol's regular production programme and water atomized iron powder AT40.29 (supplier: Höganäs AB, Sweden) with an average particle size of about 200 µm and maximum oxides content of 0.2 wt%.

The proposed cored wire, Fig. 1, consists of a porous iron powder core and a thick aluminium plate cladding. Wire is produced by the traditionally welding technique.

To design the cored wire, the following two requirements should be considered:

1. the unit length of the core (e.g. 1m) should contain a the unit mass of iron (e.g. 0.5 kg), which is most convenient for alloying practice,
2. due to cost reasons, the percentage of aluminium in the cored wire, w_{Al}, should be minimal (equal or lower than 10 wt. %).

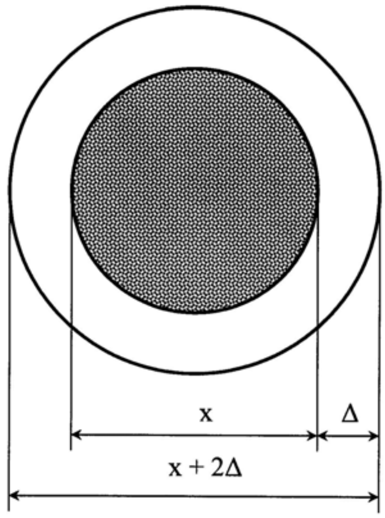

Fig. 1: Schematic presentation of the cross section of cored alloying wire consisting of an iron powder compressed core and aluminium sheet cladding

The technical characteristics of cored wire specified are: the outside and the internal diameter, as well as the mass of unit length of core or the mass of iron in unit length of cored wire.

Assuming that x is the internal diameter of the porous core of the wire and p is the porosity of the core: then the mass of the core per unit length, which we selected to be 0.5 kg, could be expressed by the following relation (Eq.3):

$$x^2\pi\ (1-p)\ 7800/4 = 0.5\ kg/m \tag{3}$$

According to the requirement that the portion of aluminium in the cored wire, w_{Al}, should not exceed 10 wt%, the portion of iron, w_{Fe}, must be equal or higher than 90 wt%:

$$w_{Fe} = 0.5\ kg/m : (0.5\ kg/m + y\ kg/m) \geq 0.9 \tag{4}$$

where y (kg/m) represents the mass of unit length of Al cladding.

By solving Eq.4, it is found that $y \leq 0.0555$ kg/m.

Finally, if we consider that Δ is the cladding wall thickness, the internal diameter of welded tube would be x+2Δ. Hence, for the mass of unit length of Al cladding one can write:

$$y = [(x+2\Delta)^2 - x^2]\ \pi\ 2700/4 \leq 0.0555\ kg/m \tag{5}$$

Results and discussion

The intermetallic inclusions originated from iron alloying additives

In order to example the appearance of intermetallic inclusions, originated from iron alloying additives, the naturally solidified AA8011 samples, taken inside the EMP tube on the occasion of its replacing with the new one, were cut, polished and investigated by SEM.

As evident from Fig. 2, the two differently coloured intermetallic inclusions - grey and light were found to be predominating in the solidified aluminium matrix. The grey inclusions (Fig. 3) are large, 10-50 μm in size, needle-shaped aggregates with dendritic intrinsic structure, while light ones (Fig. 4) appears in the form of fine monolithic particles with an average particle size less than 10 μm.

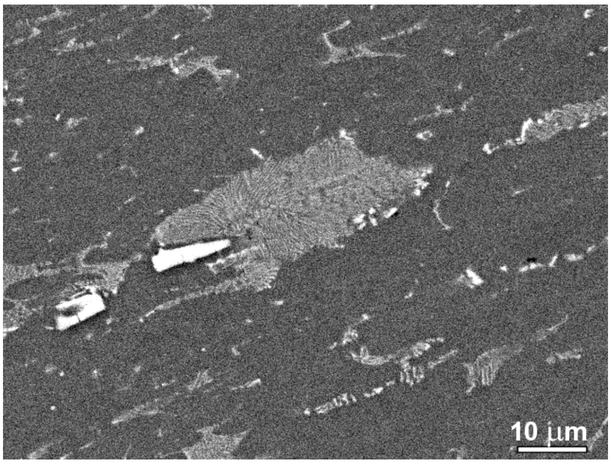

Fig.2: SEM micrograph of grey intermetallic inclusions in the form of needle-shaped aggregates and white ones in the form of monolithic particles.

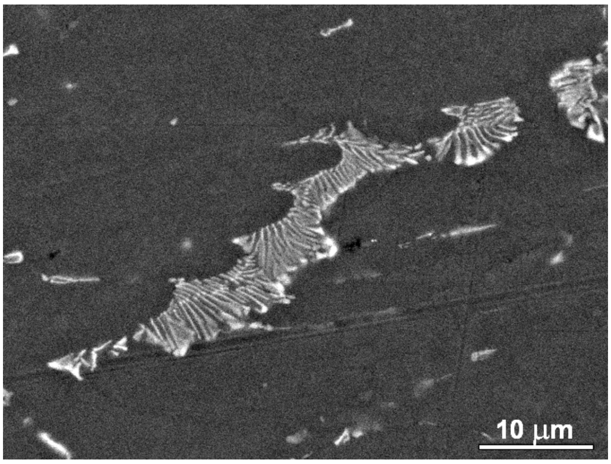

Fig.3: SEM micrograph of isolated grey intermetallic inclusion with dendirtic intrinsic structure.

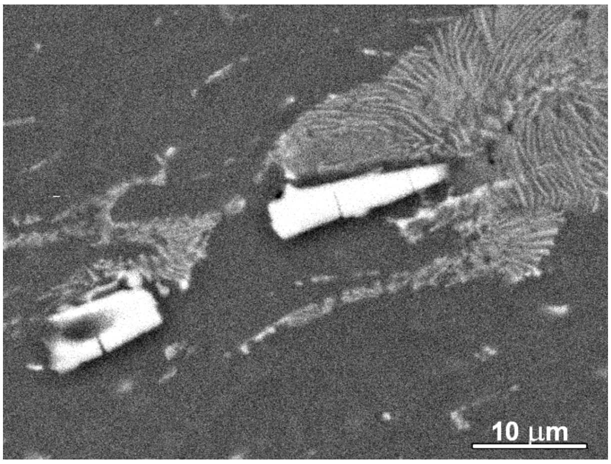

Fig. 4: SEM micrograph of individual light inclusion.

According to the data in Table 1, both grey and light inclusions have the same *qualitative* chemical composition consisting of aluminium, iron, silicon and oxygen. However, considering the *quantitative* chemical composition of these phases, the concentration of oxygen in light inclusions is two times higher in grey ones. The increasing of silicon content (for about 25%) has been also observed.

Table 1: The SEM quantitative analysis of grey and light intermetallic inclusions, detected in the solidified samples of aluminium alloy taken inside the EMP tube

Elements	Composition (at. %)	
	Grey phase	Light phase
Al	88,0	83,2
Fe	4,6	4,7
Si	3,1	4,0
O	4,3	8,1
Total	100,0	100,0

In samples taken from the EMP tube, the markedly orientation of both grey and light intermetallic inclusions along the molten aluminium flow direction through the EMP tube has been observed, Fig. 5, which is most probably caused by the intensive flow of the molten metal through the EMP tube.

To demonstrate the possible influence of such intermetallic inclusions on the quality of the final products, the SEM analysis of continuously cast aluminium strip samples were also performed. As the result, morphologically *the same* intermetallic phases, needle-shaped grey one and light, fine dispersed particles were detected, Fig. 6. The identity of intermetallic phases was additionally confirmed by SEM quantitative analysis, approving the same chemical composition of compared phases.

Based on this, one can conclude that the intermetallic inclusions are formed during iron alloying and could influence the quality of the final products.

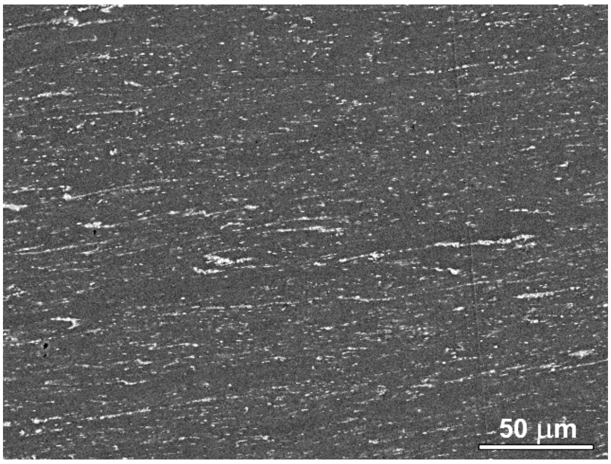

Fig. 5: SEM micrograph of the solidified aluminium alloy sample taken from the EMP tube. The markedly orientation of both grey and light inclusions along the molten aluminium flow direction through the EMP is well emphasized.

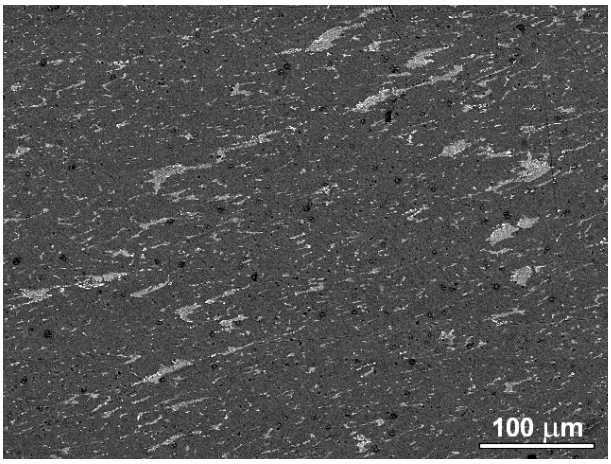

Fig. 6: SEM micrograph of the continuous cast aluminium strip sample demonstrating the presence of the same grey and light intermetallic phases.

Practical example of cored wire design

Let propose a standard thickness for the cladding (Δ = 0.5 mm) and the most convenient porosity of the core (p = 0.4). Then, from Eq.3, one can calculate that the internal diameter of the porous core should be: x = 11.66 mm. In addition, from Eq. 5 we obtain y = 0.05157 kg/m, resulting in w_{Fe} = 0.9065, which is even slightly better than the projected 0.0555 kg/m.

If the alloying time is projected to be 30 min and approximately 80 kg of iron should be introduced into the melt, then the actual alloying speed of cored wire introduction into the melt should be 5.33 m/min.

The prototype cored wire with the cladding thickness 0.5 mm, the core diameter 11,6 mm, and the core porosity of 40% was successfully produced on a semi-industrial level (Fig.7) and applied for continuous and fully automatically alloying of iron into a molten aluminium (Fig.8).This was accomplished through the charge-well of an electromagnetic pump installed on 40t melting capacity twin chamber furnace. In these industrial trials, an alloying speed of 10-11 m/min has been successfully demonstrated.

Fig. 7: The prototype cored alloying wire used for an experimental industrial trial.

Fig.8: The detail of continuous and fully automatically alloying of iron through the charge-well on an electromagnetic pump installed on the twin chamber melting furnace. During that trial, an alloying speed of 10-11m/min (approx. 5 kg/min) of iron was routinely achieved.

Some of the main advantages of cored alloying wire

The concept of cored wire has several advantages. The usage of cored wire enables a continuous mode of alloying, during which preheating and dissolution of iron particles occurs simultaneously in one single step. Preheating occurs during melting of the Al cladding. Because the Al cladding fully encapsulates the iron particles, oxidation during storage and preheating is completely excluded. In comparison with injection, where individual particles are often rejected from the melt due to unsuitable wetting conditions, the wetting of iron particles in the core region of the wire could be improved by adding various salt flux additives. Although similar or even identical additives are also used in briquettes and tablets, the wetting improvement in cored wire is significantly higher. The reason is that in cored wire these agents melt during melting of the cladding, leaching and cleaning the surface of the iron particles *before* molten aluminium wets the core region and surface of individual iron particles. In contrast, in briquettes and tablets, the wetting agents melt in parallel with the heating of the iron particles and infiltration of molten aluminium into the porous skeleton of the briquettes or tablets.

In addition, the mechanism of porous iron core dissolution in cored wire differs from the dissolution of individual iron particles injected into a melt. In the case of a porous core consisting of pressed iron particles, disassembly and dissolution of the *static* core occurs by leaching with the stirred melt. On the contrary, in the case of injected particles, dissolution occurs since the particles move along the vortex line of force having *the same* local speed as the molten metal, in that way minimizing the leaching effect.

It is also important to note that the mass of iron alloying additive introduced per second by cored wire is usually 1/5 or even 1/20 of the mass of briquettes or tablets. Accordingly, the local concentration of iron in the boundary layer between the cored wire and the molten metal is below the critical value, reducing formation of undesired intermetallic compounds.

Alloying economy

Regarding the cost of cored wire, it is definitely slightly higher than the cost of other commercial iron alloying additives (tablets, briquettes), though depending on the quality of the applied iron powder, geometry (internal diameter of the porous core, and thickness of the cladding) and the porosity of the core, as well as the alloy selected for the cladding. Generally, the production cost of cored wire amounts to one third of its total cost while the cost of the iron powder and aluminium used for cladding is about two thirds of the total cost. However, a significant cost reduction could be achieved by optimizing all the above mentioned parameters. As a result, well-optimized cored wire could become competitive (taking into consideration the other benefits listed below) with the cost of other iron alloying additives currently available on the market.

The main benefits of iron alloying in the form of cored wire are:

- fully automatic alloying,
- high iron alloying rate (about 200-300 kg/h),
- achieving a high (almost theoretical) yield of alloying additive,
- preventing of any oxidation of iron during alloying,

- significantly lower oxidation of molten aluminium during the melting cycle, as result of alloying without the need to open the door of the main chamber of the melting furnace.

Conclusion

In applications where the high alloying rate of ferrous additives represents a bottleneck in production, as well as for some particular and demanding semi- and end-products where high alloying standards are necessary for achieving a uniform and appropriate quality of products, the automatic alloying of ferrous additives with cored wire could in future become a technical and economical alternative to the existing alloying additives.

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