



Recycling of aluminium swarf by direct incorporation in aluminium melts

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ARTICLE INFO

Article history:

Received 7 November 2008

Received in revised form 8 March 2009

Accepted 12 March 2009

Keywords:

Recycling
Environment
Aluminium
Swarf

ABSTRACT

The purpose of this work was to recover a standard AlSi12Cu1 alloy from machining chips inside the foundry plant, by using an environmentally friendly technique to produce cast ingots with characteristics similar to those of the commercially available 2nd melt raw material.

The recyclability of aluminium swarf using different melting techniques and the influence of chips preparation in the aluminium alloy recovery rate and dross production was experimentally studied and evaluated.

It is shown that the recycling efficiency depends on the swarf conditioning for melting, the melting technique and the metal treatment methodology. Chips moisture reduction, induction melting under protective atmosphere and a specially developed degassing technique were found the most important factors influencing the recycling process. By using the developed technique, cast ingots with microstructure, sanity and chemical composition similar to commercially available AlSi12Cu1 2nd melt raw material were successfully obtained with minimum dross formation and metal recovery rates around 90%, without using traditional salts and fluxes.

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1. Introduction

1.1. Economical and environmental aspects of aluminium recycling

Presently most of the aluminium castings are sold as ready to use components and functional parts, with high added value, after several machining operations, which are usually carried out in machine shops inside the foundry companies themselves.

Machining operations usually generate considerable amounts of waste in the form of chips (usually 3–5% of the casting weight). Traditionally, swarf is sold to scrapers and remelters, but this option is quite expensive because the selling price is roughly 30% of the acquisition price of the commercial 2nd melt raw material. Moreover, the nonexistence of aluminium remelters in Portugal presents an additional problem for swarf alienation, which is usually sold to Spain, involving high transport costs and the need of complex waste management systems.

Moreover, reduction of the primary resource use, pollution control and prevention and sustainability policy became the focus points of modern industrial societies (Logozar et al., 2006). According to Legartha (1996), without an intensified focus on recycling, we cannot hope to fulfil even the most modest ambitions for sus-

tainability in the use of metal primary resources in the future. Furthermore, high energy savings are associated to aluminium scrap/swarf recycling as it requires not more than 5% of the energy needed for primary aluminium production (Verran and Kurzawa, 2008).

Thus, besides a direct economical problem that machining and foundry companies have to face, waste prevention and recycling are becoming critical aspects of the aluminium industrial activities, arising as aggregate phases of the production cycle.

During the last years, several recycling methods of machining chips and other aluminium wastes like beverage cans, for example, have been reported. They are based either in solid state transformation into extruded and sintered products (Samuel, 2003; Gronostajski and Matuszak, 1999; Gronostajski et al., 2000; Fogagnolo et al., 2003; Chmura and Gronostajski, 2006) or involving melting operations (Rabah, 2003; Verran and Kurzawa, 2008; Xiao and Reuter, 2002; Tenorio and Espinosa, 2002). Nevertheless, no matter the recycling method, the use of fluxes still is common practice.

1.2. Melting of aluminium swarf

For most aluminium foundries, reusing aluminium chips as raw material for the melting stocks is perhaps the best option as waste management policy in what concerns to economical and technical aspects. In house aluminium swarf recycling presents some significant benefits over other recycling solutions, namely:

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- Reduction on buying costs of raw material;
- Elimination of swarf transport costs;
- Simplified waste management system;
- High cost /benefit ratio.

Aluminium swarf is a low density product (0.25 kg/dm^3) and is usually covered by a thin film of aluminium oxide and machining fluid. Melting such a product without suitable previous preparation would lead to several problems of different nature:

- (i) Economical aspects: very low metal recovery rate and high energy consumption;
- (ii) Environmental aspects: high smoke and gases generation;
- (iii) Quality aspects: low quality of the final product (non-metallic inclusions, gas porosities, poor mechanical properties)

Although aluminium swarf recycling is usually associated to economical and environmental factors, the inclusion of the final product in the production chain cannot lead to a decrease in the quality standards of the manufactured parts. To accomplish that demand, and due to its low density and high contamination, traditional aluminium swarf recovery is performed using high environmental impact fluids and fluxes, both for previous swarf conditioning operations and the liquid metal treatment. Besides, the actual procedure generates dangerous residues that the remelting companies must alienate, usually at high cost, even if some valorization techniques are arising (Shinzato and Hypolito, 2005).

Recycling of aluminium alloys swarf by melting requires several operations in order to achieve good ingot quality standards: swarf conditioning (cleaning, drying and compaction), melting, molten metal treatment (degassing, grain refinement and microstructure modification) and ingot production.

Traditionally remelters use a degreasing fluid to clean the machining swarf followed by a heating operation to dry it, which often leads to the development of new oxide films. The melting operation is usually performed in high energy consumption fossil fuel rotary furnaces, using up to 20% addition of low melting point salts based in equimolar mixtures of potassium and sodium chlorides to improve de-oxidation, as well as fluorides in the form of CaF_2 and Na_3AlF_6 (Tenorio and Espinosa, 2002). The liquid salts break the oxide structure and transform the oxide net in a great number of small fragments that turn into the shape of plates or small clusters of plates. The aluminium freed from the oxides start to coalesce generating small drops of liquid that start to coalesce themselves and grow. The oxide-salt reaction generates a by-product, known as “salt-cake” (Gruzleski and Closset, 1990), which is considered a hazardous waste.

Table 1

Experimental conditions used on stage 1 of this work.

Set	Experiment	Furnace	Briquetting pressure (bar)	Atmosphere	Quantity of swarf briquettes in the melting stock (%)	Melting temperature ($^{\circ}\text{C}$)
1	1	Induction	400	Argon	33.3	850
	2	Resistance	400	Argon	33.3	850
	3	Induction	400	Argon	33.3	800
	4	Resistance	400	Argon	33.3	800
2	5–7	Induction	400	No protection	33.3	850
	8–10	Induction	400	Argon	33.3	850
3	11–13	Induction	400	Argon	33.3	800
	14–16	Induction	400	Argon	33.3	900
	17–19	Induction	400	Argon	33.3	950
4	20–22	Induction	300	Argon	33.3	850
	23–25	Induction	500	Argon	33.3	850
5	26–28	Induction	300	Argon	50	850
	29–31	Induction	300	Argon	66.7	850
	32–34	Induction	300	Argon	80	850

After melting, the liquid metal is degassed and refined using suitable products for each type of alloy, normally TiB_2 and Al10Sr (Gruzleski and Closset, 1990), and poured into metallic moulds.

At the end, aluminium loss can easily reach 50% (Samuel, 2003), making this traditional recovery procedure highly inefficient.

The objective of this work was the development of an environmentally friend aluminium swarf recycling technique avoiding the use of salts during melting, by using induction melting and performing degassing by a novel ultrasonic technique. Those techniques and procedures are the major advantages in the current industrial practice. In order to attain considerable decreasing into manufacturing costs, the final recovered product is introduced in the production cycle together with remaining raw materials.

2. Experimental procedure

This work included 2 different stages, according to the envisaged objectives:

- (1) Establishment of the optimal melting conditions (swarf conditioning, furnace type and melting atmosphere, melting temperature and melting stock composition) which lead to the highest metal recovery rate;
- (2) Establishment of the best molten metal treatment route (degassing, grain refinement and eutectic silicon modification) that leads to homogeneous resulting microstructure and consequently increases the resulting mechanical properties of as-cast alloy samples.

Stage 2 was carried out after finishing every steps of stage 1, and using the best conditions established in this stage.

To accomplish the envisaged objectives, different tasks were scheduled integrating 5 sets of experiments in stage 1 (Table 1) and were experimentally developed according to the following methodology:

2.1. Stage 1 – Swarf melting procedures

2.1.1. Swarf conditioning

After machining the swarf was allowed to decant for 12 h, to decrease the moisture content, and centrifuged for 10 min at 400 rpm. After this operation it was compacted in $50 \times 50 \times (\approx 90)\text{mm}$ briquettes using 300, 400 and 500 bar.

2.1.2. Melting operation

Melting was performed in a 1500 Hz, 50 kW, 10 l induction furnace using a SiC crucible as lining. For the sake of comparison,

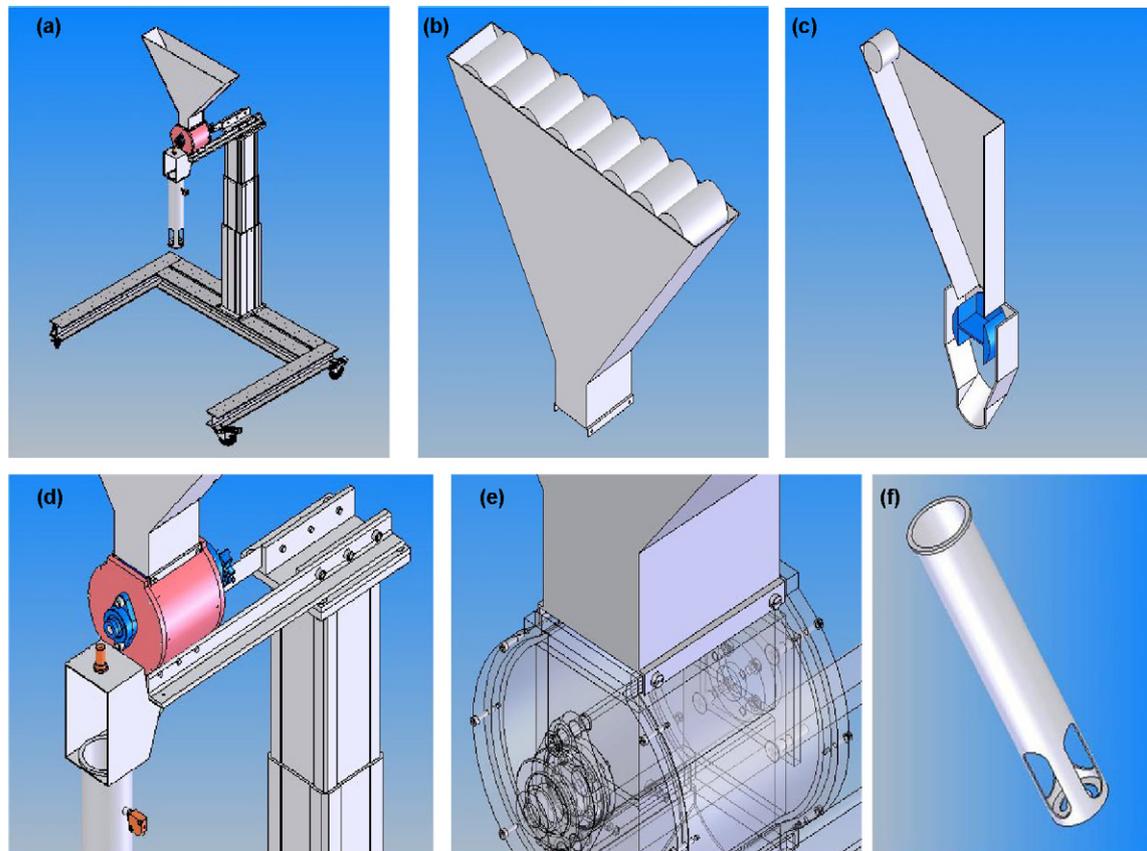


Fig. 1. Schematic representation of the automatic briquette feeder. (a) overview; (b) and (c) briquette silo; (d) and (e) briquettes rotation device; (f) Tungsten carbide tube for briquette immersion and positioning during melting.

melting was also performed in a 15 kW electric resistance furnace equipped with a SiC crucible of the same capacity.

In both cases, a 5 kg molten bath of AlSi12Cu1 was produced using commercially available 2nd melt ingot. Briquettes were then introduced inside the molten pool using a specially designed automatic feeder (Fig. 1) that allowed the swarf briquettes to completely melt inside the liquid, without contact with the furnace atmosphere.

The total size of the melting stock was about 15 kg in every experiment. Total melting time after inserting the first briquette varied from 50 to 70 min in the induction furnace and from 65 to 120 min in the electrical furnace, depending on the compression strength used for briquetting and the melting temperature. Melting temperatures of 800, 850, 900 and 950 °C were evaluated, which were kept quite constant during the entire melting, and for 10 min after melting the last briquette. For the sake of comparison, melts were performed using both argon protected and non-protected atmospheres.

2.1.3. Melting stock composition

After characterizing the most suitable melting furnace/technique, experiments were carried out in the induction furnace, using the same approach as described in section b), but using different volumes of initial molten pool (only AlSi12Cu1 commercial 2nd melt ingot) – 20% to 66.7% – in order to evaluate the influence of this parameter in the metal recovery rate and dross formation (see Table 1)

2.2. Stage 2 – Melt treatment techniques

2.2.1. Degassing operation

After melting and 10 min holding time at 850 °C, the molten alloy was allowed to cool to 730 °C for degassing, grain refining and microstructure modification.

Degassing operation was performed at 730 °C using a novel ultrasonic technique (Fig. 2). The ultrasonic parameters were 19.9 kHz at 1 kW. Degassing times from 2 to 10 min were used and its influence in the hydrogen removal rate and samples density was evaluated. For the sake of comparison, argon and nitrogen degassing (injection flow of 5 l/min) using the rotary diffuser technique at 100 rpm for 4 to 10 min was also performed at the same temperature. Hydrogen content evaluation was performed using the traditional “Straube-Pfeiffer” method, also known as reduced pressure test (RPT). The molten alloy was poured into a thin-wall iron cup (≈ 120 g) and allowed to solidify under a reduced pressure of 76 mm Hg. Its density (D) was evaluated by the apparent density measurement technique, using the following equation (Neff, 1989):

$$D = \frac{W_a}{(W_a - W_w)} \quad (1)$$

where W_a and W_w are the sample weights measured in air and water, respectively.

The volume of gas (V_g) was given by Eq. (2), where D_0 is the alloy theoretical density and k is a constant for standard temperature and pressure conditions correction, given by Eq. (3). (mh).

$$V_g = k \times \left(\frac{1}{D} - \frac{1}{D_0} \right) \quad (2)$$

$$k = \left(\frac{\text{Test pressure}}{760} \right) \times \left[\frac{273}{(273 + \text{alloy freezing temperature})} \right] \quad (4)$$

2.2.2. Grain refinement and microstructure modification

It is well known that Al–Ti and Al–Ti–B master alloys can considerably provide efficient grain refinement in as-cast Al based alloys (Limmaneevichitr and Eidhed, 2003; Dahle et al., 1996) and Al–Sr alloys can promote significant silicon modification (Gruzleski and Closset, 1990). Grain refinement was performed after degassing



Fig. 2. Ultrasonic degassing equipment.

using different additions of a Al–Ti–B master alloy, corresponding to Ti additions of 0.01, 0.02 and 0.03 wt%. For the eutectic silicon modification different additions of an Al5Sr master alloy were used in posterior experiments, in order to obtain Sr additions of 0.02, 0.03 and 0.04 wt%, using melts where a Ti addition established according to the best results obtained during the grain refinement experiments (0.02 wt% Ti).

2.2.3. Microstructure characterization

In every experiment both ingots and test samples were cast for microstructure characterization and chemical analysis evaluation. Test samples were cylinders with 20 mm diameter and 80 mm length that were poured at 730 °C in permanent metallic moulds pre-heated to 250 °C. Samples for characterization were collected along the cast cylinders by sectioning them at 50% of their height. They were ground by using 1200 SiC paper, polished up to 1 μm and etched to reveal the resulting microstructure (etchant: 0.5% HF

aqueous solution at room temperature). Samples microstructure was characterized by optical microscopy.

2.2.4. Chemical composition evaluation

Chemical composition of cast alloys was determined by optical emission spectrometry using a glow discharge LECO GDS 500A spectrometer. RMC (reference materials certified) of similar chemical composition were used for calibration. For every sample, 3 measurements were performed. Results presented on the *Results* section are the average of those 3 measured values.

2.2.5. Evaluation of the aluminium recovery yield and dross generation

It was assumed that the yield of the molten pool (only 2nd melt raw material) was 100%, and that dross generation was due only to the aluminium briquettes.

3. Results and Discussion

3.1. Stage 1 – Swarf melting procedures

3.1.1. Influence of moisture content on briquettes density

The swarf moisture content attained of about 17 and 9 wt% after machining and decantation for 12 h, respectively. Depending of briquetting pressure application, the same moisture content can attain values a little less than 3 wt% (Table 2).

3.1.2. Influence of the melting furnace in the aluminium recovery rate

On the first set of experiments (1 to 4 – see Table 1) the influence of the melting furnace on the aluminium recovery rate and dross formation was evaluated, and results are presented in Table 3.

It was clearly seen that resistance furnace melting was totally inappropriate for swarf recycling. Due to the static behaviour of the molten pool inside the crucible, molten aluminium cannot break the aluminium oxide envelope that surrounds it, leading to low recovery rates (less than 60%) and high aluminium dross generation (around 30%). On the other hand, melting rate was quite low in resistance furnace, leading to melting times of almost 2 h (Table 3).

Recovery rates were higher in induction melting (around 85%), confirming previous suggestions of Smith and Hayes (1992) and Verran and Kurzawa (2008). In this case, once the molten state is achieved, the interaction of current in the melt with the electromagnetic field produces a stirring motion that leads to the destruction of the oxide films where liquid aluminium is entrapped, thus increasing the volume of molten aluminium that is recovered. The melt temperature also affected the aluminium recovery yield that was

Table 2
Influence of the briquetting pressure in the swarf moisture content and briquettes density.

Pressure (bar)	Initial weight (kg)	Final weight (kg)	Moisture content (%)	Density (kg/dm ³)
300	4.94×10^{-1}	4.80×10^{-1}	2.83	2.03
400	5.03×10^{-1}	4.90×10^{-1}	2.58	2.07
500	4.96×10^{-1}	4.84×10^{-1}	2.42	2.10

Table 3
Influence of the melting furnace in the aluminium recovery rate and dross generation, for 800 (3 and 4) and 850 °C (1 and 2) melting temperatures and 33.3% briquettes in the melting stock.

Experiment	Furnace	Melting charge (kg)			Poured (kg)			Metal incorporation [(4 – 1)/2] × 100		Dross (5/2) × 100
		Ingot (1)	Briquettes (2)	Total (3)	Metal (4)	Dross (5)	Total (4 + 5)	(%)		
1	Induction	9.5	4.7	14.2	13.5	0.45	13.95	85.1	9.6	
2	Resistance	9.6	4.8	14.4	12.9	1.30	14.20	68.8	27.1	
3	Induction	9.6	4.8	14.4	13.6	0.55	14.15	83.3	11.4	
4	Resistance	9.4	4.8	14.2	12.4	1.55	13.95	62.5	32.3	

Table 4

Influence of the melting atmosphere in the aluminium recovery rate and dross generation, for 850 °C melting temperature and 33.3% briquettes in the melting stock.

Experiment	Atmosphere	Melting charge (kg)			Poured (kg)			(%)	
		Ingot (1)	Briquettes (2)	Total (3)	Metal (4)	Dross (5)	Total (4+5)	Metal incorporation [(4 - 1)/2] × 100	Dross (5/2) × 100
5	No protection	9.3	4.7	14.0	12.2	1.53	13.53	61.7	32.5
6	No protection	9.1	4.6	13.7	11.8	1.60	13.40	58.7	34.8
7	No protection	9.9	5.0	14.9	13.0	1.70	14.70	62.0	34.0
8	Argon	9.6	4.8	14.4	13.7	0.56	14.26	85.4	11.7
9	Argon	9.6	4.8	14.4	13.5	0.63	14.13	81.3	13.1
10	Argon	9.6	4.8	14.4	13.6	0.65	14.25	83.3	13.5

Table 5

Influence of melting temperature in the aluminium recovery rate and dross generation for 33.3% briquettes in the melting stock.

Experiment	Temperature (°C)	Melting time (minutes)*	Melting charge (kg)			Poured (kg)			(%)	
			Ingot (1)	Briquettes (2)	Total (3)	Metal (4)	Dross (5)	Total (4+5)	Metal incorp. [(4 - 1)/2] × 100	Dross (5/2) × 100
11	800	65	9.5	4.4	13.9	13	0.68	13.68	79.5	15.5
12	800	65	9.5	4.5	14.0	13.1	0.65	13.75	80.0	14.4
13	800	65	9.3	4.4	13.7	12.9	0.62	13.52	81.8	14.1
14	900	55	9.6	4.6	14.2	13.5	0.54	14.04	84.8	11.7
15	900	55	9.5	4.6	14.1	13.3	0.56	13.86	82.6	12.2
16	900	55	9.6	4.5	14.1	13.4	0.57	14.01	84.4	12.7
17	950	50	9.6	4.5	14.1	13.3	0.52	13.82	82.2	11.6
18	950	50	9.6	4.4	14.0	13.4	0.59	14.01	85.2	13.4
19	950	50	9.4	4.5	13.9	13.2	0.52	13.72	84.4	11.6

* After introducing the 1st briquette.

higher for 850 °C, for both furnaces (experiments 1 and 2), confirming the results of Verran and Kurzawa (2008) for the same temperature range.

3.1.3. Influence of the melting atmosphere in the aluminium recovery rate

The melting atmosphere can play an important role in the aluminium recovery yield, mainly if melting is conducted in induction furnaces. Due to the stirring effect of the electromagnetic field, the surface of the molten alloy is in constant movement. Stirring of the melt, mainly when associated to high holding temperatures, significantly increase the rate of hydrogen solution, oxidation and transient element loss. Thus, stirring can significantly provide a dendritic refinement due to liquid movement and recalescence of Al-rich phase and eutectic mixture (at mushy zone) which can decrease the oxide film kinetics between Al and remained hydrogen and/or oxygen-free. However, it is well known that hydrogen has a high solubility in aluminium and its alloys, which decreases very fast during cooling. As a consequence, the excess of dissolved hydrogen may precipitate in molecular form, resulting in the formation of primary and/or secondary voids. For such reasons, the use of protective argon or nitrogen atmospheres during melting is a crucial factor to decrease the probability of hydrogen and oxygen pickup by the molten aluminium and to increase the aluminium recovery rate.

In Table 4 the effect of the melting atmosphere in the aluminium recovery rate is presented. The use of a protective argon atmosphere increased the aluminium recovery rate in more than 37% (from an average value of 60.8% – exp 5–7 – to an average value of 83.3% – exp 8–10). The use of inert atmosphere also avoided metal-air contact at the surface of the pool, decreasing oxidation and strongly reducing dross generation (see Table 4).

3.1.4. Influence of the melting temperature in the aluminium recovery rate

There are several factors associated to the kinetics of oxide generation during aluminium recycling, which is one of the main factors affecting the yield of the recovery process and the amount of generated dross. In this context, the melt temperature is perhaps the most critical parameter.

On the 3rd set of experiments (experiments 11–19 – see Table 1) the influence of melt temperature in the aluminium recovery rate and dross formation was evaluated, and the results are presented in Table 5.

It was found that for temperatures below 850 °C both the Al recovery rate and the amount of dross generated were strongly influenced by the maximum cycle temperature. Higher melt temperatures correspond to higher recovery rates and lower dross generation (see Fig. 3 – data corresponds to results of experiments 8–19).

For temperatures higher than 850 °C, the aluminium recovery rate and dross generation did not change significantly with temperature, however the briquettes melting time decreased with the increase of that parameter (see Tables 4 and 5).

Nevertheless, the increase in energy consumption associated to the use of higher temperatures may be detrimental in the economical point of view.

3.1.5. Influence of the briquetting pressure in the aluminium recovery rate

The use of compacted swarf in melting stocks and its melt inside the molten pool is the best way to increase the metal recovery rate from machining chips. Otherwise, the high volume-to-weight

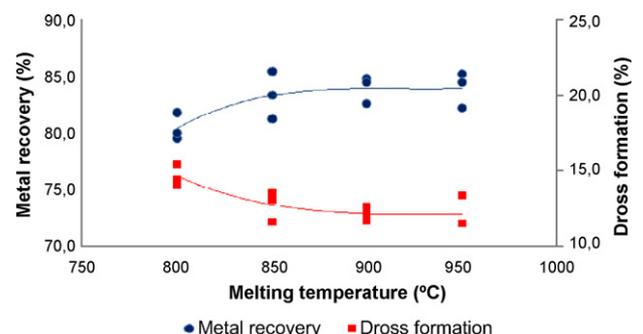


Fig. 3. Influence of the melting temperature on the metal recovery rate and dross generation.

Table 6
Influence of briquettes compaction pressure in the aluminium recovery rate and dross generation, for 850 °C melting temperature and 33.3% briquettes in the melting stock.

Experiment	P (bar)	Melting time (minutes)*	Melting charge (kg)			Poured (kg)			Dross (%)	
			Ingot (1)	Briquettes (2)	Total (3)	Metal (4)	Dross (5)	Total (4+5)	Metal incorp. [(4-1)/2] × 100	Dross (5/2) × 100
20	300	55	9.9	5.1	15	14.4	0.45	14.85	88.2	8.8
21	300	55	9.3	4.6	13.9	13.5	0.37	13.87	91.3	8.0
22	300	55	9.6	4.8	14.4	13.9	0.43	14.33	89.6	8.9
8	400	60	9.6	4.8	14.4	13.7	0.56	14.26	85.4	11.7
9	400	60	9.6	4.8	14.4	13.5	0.63	14.13	81.3	13.1
10	400	60	9.6	4.8	14.4	13.6	0.65	14.25	83.3	13.5
23	500	70	9.5	4.6	14.1	13.1	0.8	13.9	78.3	17.4
24	500	70	9.6	4.8	14.4	13.3	0.7	14.0	77.1	14.6
25	500	70	9.4	4.8	14.2	13	0.9	13.9	75.0	18.8

* After introducing the 1st briquette.

ratio of the swarf will make it to float at the top of the liquid pool increasing the probability of new oxide skin formation.

Experiments with briquettes compacted at different pressures were carried out in the induction furnace. The best recovery rates were obtained for the lowest compaction pressure and decreased as the compression pressure raised (Table 6 – experiments 8–10 and 20–25). This can be explained by different briquettes porosity levels associated to different compression values – higher briquetting pressures lead to lower porosity levels in the briquettes. In those briquettes compressed at 300 bar, the molten metal could easily penetrate the interstitials between the swarf fragments, making the swarf melting easier and faster. This was confirmed by the lower melting time when those briquettes were used (see Table 6).

Metal penetration was more difficult in those briquettes compressed at 500 bar and, as a consequence, the melting time was higher. In fact, the high volume of dross generated when those briquettes were used suggests that the melting time was probably not enough, and dross still contained a significant metal fraction. The recovery rate could probably be increased by increasing the total melting time.

3.1.6. Influence of the melting charge composition in the aluminium recovery rate

When melting metallic swarf, a melting charge made of traditional ingot must be melted before introducing the swarf briquettes into the furnace. This way, swarf briquettes will melt inside the molten pool, avoiding the formation of metal oxides. The ideal size of such previously molten pool is not known, and it will depend on the briquettes shape and size, the furnace dimensions and the tools used to plunge the compacted swarf. On the 5th set of experiments (experiments 26–34 – see Table 1) molten pools of Al ingot corresponding to 20%, 33.3% and 50% of the total melting charge were used. Melting charges were completed with briquettes of Al swarf compressed at 300 bar. The highest aluminium recovery rates (approximately 90%) were obtained for initial molten pools higher than 33.3%. For small molten baths (around 20%), the recovery yield decreased until values around 85% and lower (see Fig. 4). This effect

Table 7
Influence of the degassing method in the hydrogen removal from molten baths.

Time (Minutes)	Argon			Nitrogen			Ultrasound		
	Experiment 35			Experiment 36			Experiment 37		
	$H_{initial}$ (ml H ₂ /100 g Al)	H_{final}	Reduction	$H_{initial}$ (ml H ₂ /100 g Al)	H_{final}	Reduction	$H_{initial}$ (ml H ₂ /100 g Al)	H_{final}	Reduction
	1.60			1.44			1.68		
2		n.a.	n.a.		n.a.	n.a.		0.89	0.79
4		1.30	0.30		1.18	0.26		0.45	1.23
6		0.86	0.74		0.85	0.59		0.20	1.48
8		0.53	1.07		0.64	0.80		0.17	1.51
10		0.51	1.09		0.60	0.84		0.18	1.50

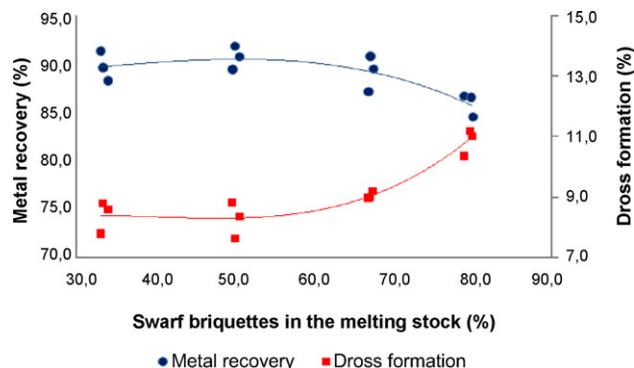


Fig. 4. Influence of the briquettes content in the melting stock on the metal recovery rate and dross.

was probably due to insufficient volume of the initial molten pool that could not avoid the contact between the briquettes and the atmosphere. As a result, swarf oxidation may have occurred leading to higher dross generation and lower metal recovery.

After these first 5 sets of experiments, it was established the optimum experimental conditions to carry on stage 2):

- Melting stock: around 15 kg (33.3% of 2nd melt raw material (initial molten pool) and 66.7% swarf briquettes compacted to 300 bar);
- Melting technique: induction melting at 850 °C in an argon atmosphere, and 60 min total melting time;

3.2. Stage 2 – Melt treatment techniques

3.2.1. Degassing

On Table 7 results of different degassing methods are presented. The new ultrasonic degassing technique is clearly more efficient in the hydrogen removal rate than any other concurrent technique based in purging gas. Using ultrasonic degassing the

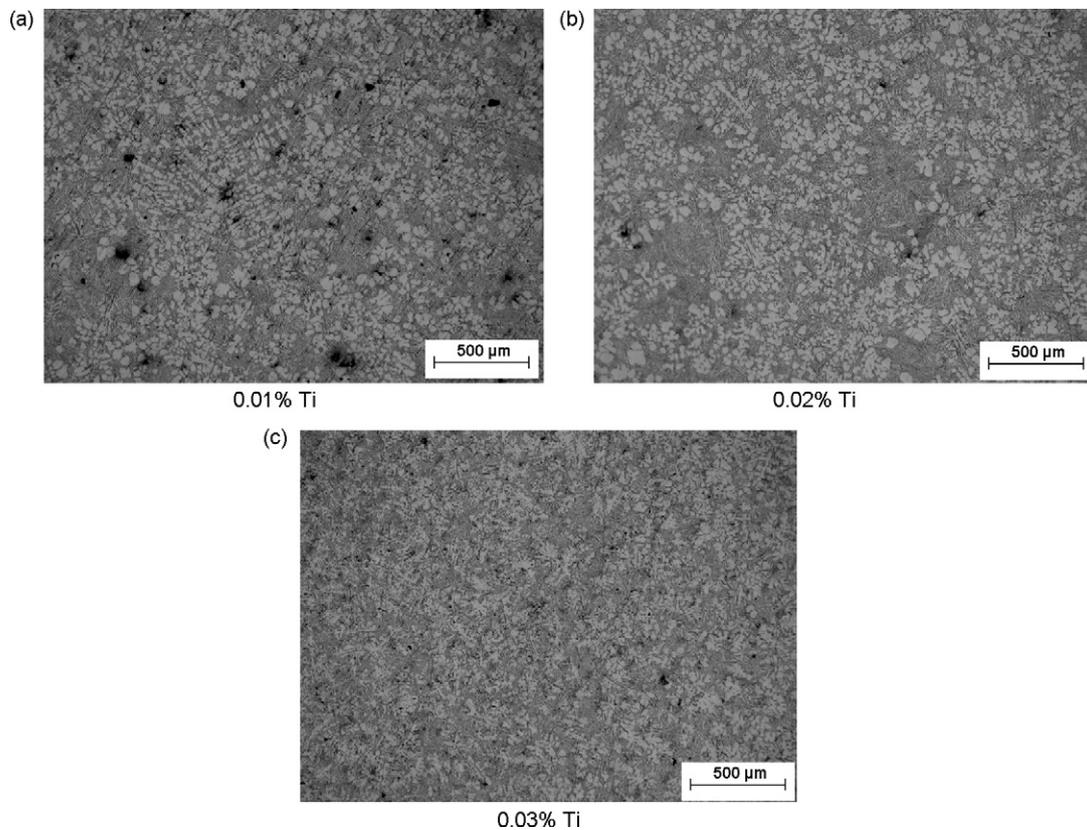


Fig. 5. Influence of Ti addition in grain refinement of an AlSi12Cu1 alloy.

amount of hydrogen removed from the molten metal after 6 min was 1.48 ml/100 g Al in experiment 37. For longer degassing times the hydrogen content of the molten baths becomes almost constant, suggesting that after 6 min the quantity of hydrogen removed using this process can be neglected. These results agree with findings of Xu et al. (2008) for ultrasonically degassed traditional melting charges of AlSi7Mg. Using the purging gas technique, the amount of hydrogen removed after the same 6 min was 0.74 and 0.59 ml/100 g Al for argon and nitrogen, respectively. Moreover, the final hydrogen content that seems to be possible to achieve by using purging gases is around 0.5 and 0.6 ml/100 g Al for argon and nitrogen, respectively. By using ultrasonic degassing, the lowest hydrogen content seems to be around 0.2 ml/100 g Al, which is around 3 times lower.

These results reveal the huge potential of ultrasonic degassing of aluminium alloys, not only in what concerns to the removal rate but also to the final hydrogen content that is possible to achieve. This efficiency is due to the development of a much higher quantity of small bubbles that are produced by cavitation in the entire volume of molten metal, when compared with the size and amount of bubbles developed by using purging gases.

3.2.2. Grain refinement and Si modification

After ultrasonic degassing for 6 min, grain refinement was performed using the techniques referred in point (e) of Section 2. In Figs. 5–7 the microstructure of cast samples obtained using different additions of Ti and Sr are presented, respectively.

There are visible differences in the microstructure of cast samples. Those samples obtained by adding 0.03 wt% Ti seem to present the most refined structure without the presence of dendrites. 0.01 wt% Ti addition reveals well developed dendrites and 0.02 wt% Ti lead to small dendrites. As expected, Al₂Cu intermetallic particles formed in the microstructure, as it can also be observed in Fig. 6.

Fig. 7 suggests that Sr addition lead to a considerable eutectic silicon modification. Its microstructural features result in fine and fibrous eutectic silicon, as a function of Sr content/addition. It is known that addition of a modifier can lead to significant changing in the morphology of the eutectic silicon. Indeed, the eutectic modifier does not affect the nucleation rate in the first stages of solidification and, consequently, the mean grain size, The dendritic array and the Al-rich dendritic matrix are unaffected, as recently reported by some researchers (Osório et al., 2007a,b and Osório et al., 2008). The extent of Si modification can be evaluated by analysis of the eutectic Si morphology. Without modification, eutectic Si exhibits acicular shape that gradually changes to lamellar and fibrous shapes with increasing modification. Fully modified structures exhibit fibrous Si

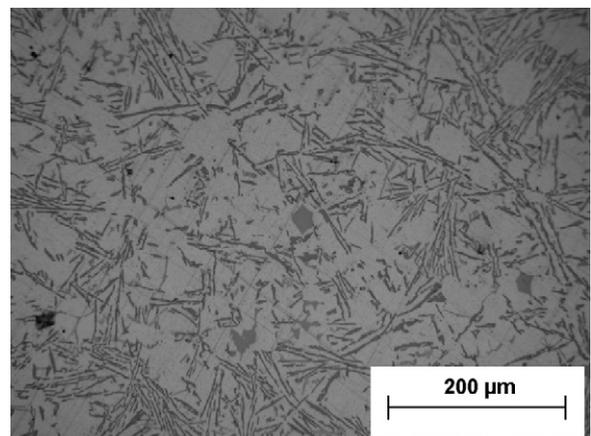


Fig. 6. Microstructure of an AlSi12Cu1 sample, revealing the presence of intermetallics, probably Al₂Cu.

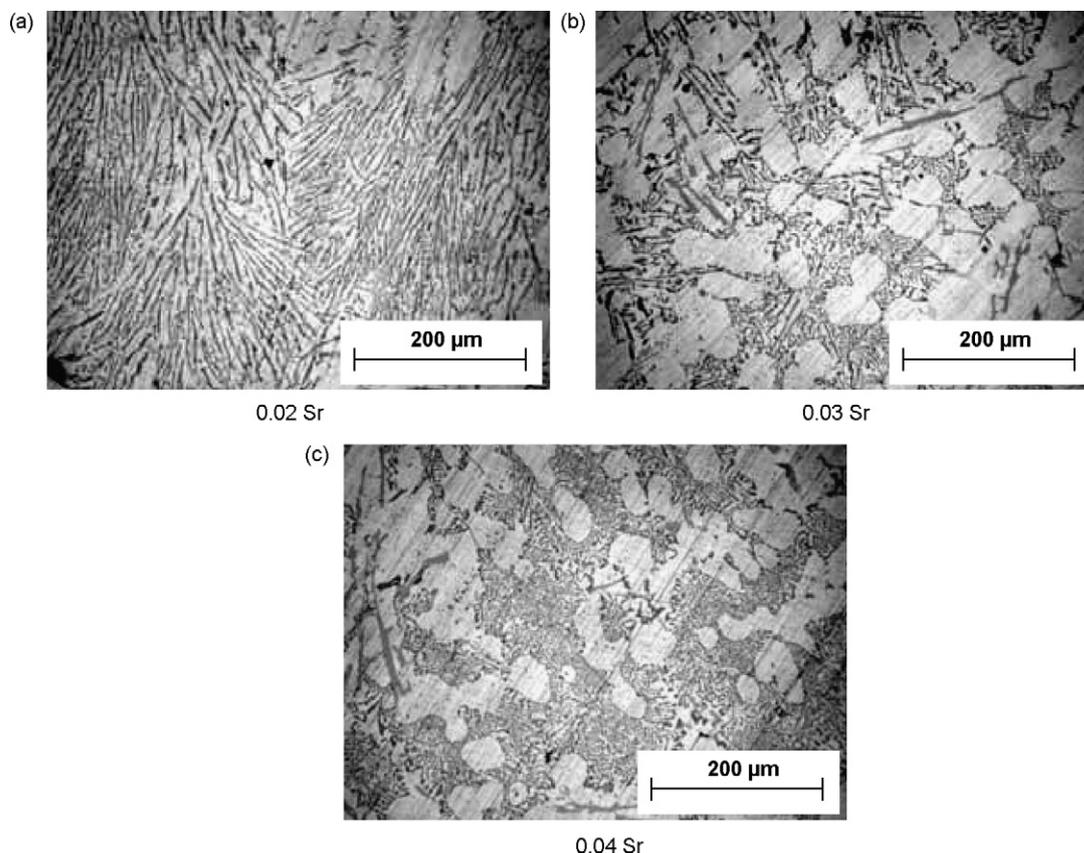


Fig. 7. Influence of the Sr addition in the eutectic silicon modification of a AlSi12Cu1 alloy.

Table 8

Chemical composition of cast alloys after different Ti and Sr additions.

Experiment	Ti ad	Sr ad	Si	Cu	Mg	Fe	Mn	Pb	Ni	Cr	Ti	Al
38	0.01	–	10.64	0.71	0.026	0.98	0.28	0.051	0.041	0.043	0.008	Bal
39	0.02	–	11.12	0.69	0.015	1.21	0.30	0.054	0.039	0.039	0.012	Bal
40	0.03	–	10.75	0.69	0.024	0.96	0.28	0.048	0.043	0.038	0.019	Bal
41	0.02	0.02	12.20	1.04	0.009	0.93	0.27	0.052	0.036	0.038	0.015	Bal
42	0.02	0.03	11.82	0.70	0.017	0.99	0.23	0.050	0.039	0.045	0.017	Bal
43	0.02	0.04	10.97	0.66	0.018	0.92	0.28	0.046	0.044	0.040	0.013	Bal
Commercial ingot	–	–	10.90	0.70	0.019	0.97	0.25	0.053	0.042	0.050	0.012	Bal
Standard alloy	–	–	10.5–12.0	0.7–1.0	0.02 max	0.8–1.0	0.2–0.3	0.08 max	0.05 max	0.05 max	0.2 max	Bal

eutectics and partially modified structures reveal a mix of Silicon lamellae and fibrous Silicon. According to Gruzleski and Closset, 1990 modified structures can be rated in 6 classes, according to the volume fraction of each elementary Si shape – lamellae, fibrous and acicular. Class 1 corresponds to acicular Si fully unmodified structures, Classe 2 shows exclusively lamellar Si and Class 3 corresponds to a mix of lamellar and fibrous Si. Classes 4 to 6 correspond to fully modified structures of fibrous Si, which become very fine in Class 6.

For the experimental conditions used on this work, 0.04 wt% Sr addition seems to be the best option (Fig. 7c), leading to a fully modified Class 4 microstructure. Fig. 7(a) (0.02 wt% Sr) shows a Class 2 unmodified structure, with dispersed Si lamellae in an aluminium matrix, while Fig. 7(b) shows a partially modified Class 3 microstructure with still some dispersed Si lamellae.

Both grain refinement and eutectic modification processes can affect on the oxidation and hydrogen and similar nature gases formation. The control resulting refined and modified microstructures can be used in aluminium foundry companies in order to avoid dross formation and contribute to environmental recycling swarf.

3.2.3. Chemical composition

Table 8 presents the chemical composition of cast samples determined by optical emission spectrometry, and the composition of a cast sample obtained exclusively with commercial 2nd melt AlSi12Cu1 ingot. Results are quite similar, no matter the metal treatment parameters that were used, and no significant differences to the composition of cast alloys obtained with commercial ingot and the ingot standard composition itself were found.

4. Conclusions

An efficient and environmentally friend swarf recycling technique was developed, and is ready for widespread dissemination. Among other minor important conclusions, it must be referred:

- The swarf conditioning, namely its moisture content and a suitable compression pressure are crucial factors to achieve high metal recovery yields;
- The use of induction melting leads to recovery yields around 90%, which are the highest values referred so far;

- The melting temperature is a crucial factor in dross formation and metal recovery rate, with the best values being achieved for 850 °C;
- The use of a suitable volume of molten metal bath, allowing the aluminium swarf to be melted without contact with the atmosphere is a significant factor to avoid dross formation;
- Up to 80% the amount of swarf in the melting stock does not affect the metal recovery yield;
- Traditional grain refinement and silicon modification techniques can be successfully used when melting aluminium swarf;
- The recycled aluminium alloy presents a chemical composition according to the expected standards and similar to that obtained using exclusively commercially ingot as melting stock, and the generated dross is free from salts and fluxes.

Acknowledgments

The authors wish to thank Agência de Inovação and Kupper and Schmidt for the financial support of this work, and the University of Minho, where the work was developed.

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