Aluminum Scraps Recycling Melting Furnace Manufacturer

Aluminum Scraps Recycling Melting and Process

Abstract

Aluminum recycling is an excellent example in the efficient utilization of secondary material resources. During secondary Aluminum recovery, Aluminum scraps are melted and refined often in a rotary melting furnace under a molten salt layer, as a European practice. The feed is normally a complex combination of Aluminum scraps with different types, sizes, shapes, compositions, and contaminations. Efficient melting of the scrap is a critical issue in order to achieve higher metal recovery, lower energy and salt consumption, and less environmental impact. In the present paper, melting behaviour of various types of Aluminum scraps was investigated in laboratory furnaces. The recyclability of different scraps was examined. It confirms that scrap type, surface conditions, size and contaminants have significant influence on the metal yield and scrap recyclability. Based on the experimental results and industrial operational data, a CFD based process model has been developed, coupled with user-developed sub-models for scrap-melting and metal burn-off. The distributed melting behaviour of different Aluminum scraps was evaluated and the modelling results were used to analyse the melting process in industrial furnace, and to estimate the energy flow and distribution, and finally contribute to process optimisation.

1. Introduction

Recycling of Aluminum has great advantages over primary Aluminum production due to its lower cost and less energy consumption. It plays more and more important role in the overall Aluminum supply. The share of the secondary Aluminum production has been constantly growing worldwide, and recently increased to over 40% in western Europe.

Secondary Aluminum has been used in a number of areas, for example in transportation, building, and packaging industries. Generally speaking, there are two types of Aluminum scraps: new or production scrap and old scrap. The new scrap comes directly from the manufacturing and fabrication processes. They are easy to recycle and are almost 100% directly remelted with little preparation. The old scrap comes from various sources and is normally contaminated with foreign elements and organics.

The most important part in a secondary Aluminum industry is the melting process, which is normally processed in a rotary furnace or a hearth furnace. Fig.1 shows a typical secondary Aluminum recycling with the rotary furnace process. The whole recycling process can be divided into several steps: collection of scrap, pre-treatment/preparation of scrap, melting of scrap in rotary furnaces, refining and alloying of liquid Aluminum in holding furnaces, casting or transportation to the industrial end-users. Salt flux is used to protect from burning of Aluminum metal and to absorb and remove contaminants and oxides. Natural gas is burned with oxygen as heat source. The furnace keeps rotating to mix the scrap and the melts. The operation temperature is normally around 800^{o}C. The chemical composition of the molten metal product is controlled not only by the process operation, but also to a great extent by proper scrap selection. Metal loss is a crucial factor in Aluminum scrap recycling, which depends very much on the recyclability of the selected Aluminum scrap. To provide the basic knowledge of different scraps for recycling, the melting experiments of various Aluminum scraps were carried out to evaluate the recycability of the scraps, and to understand the melting behaviour of scrap metal in molten melts. In addition, to provide guidance for process improvement, a process model was developed based on Computational Fluid-dynamics (CFD) to predict the melting rate and energy distribution in relation to the scrap types and operation parameters.

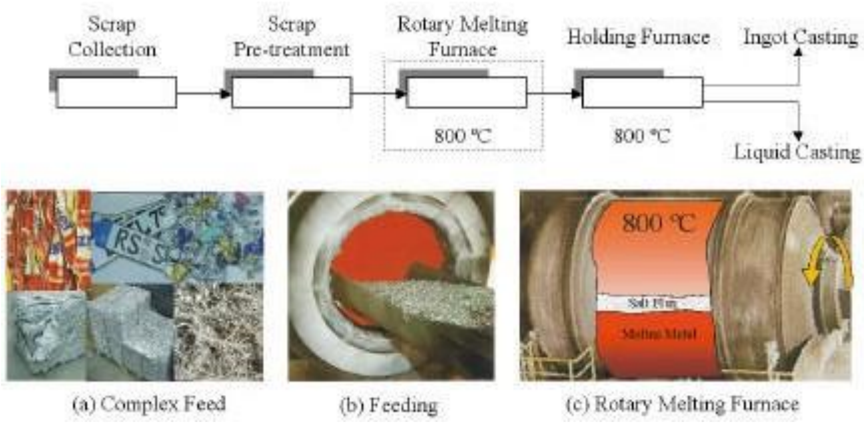


Fig. 1: A typical secondary Aluminum recovery process with a rotary furnace

2. Experimental

In order to get a better understanding of the scrap characteristics and its melting behaviour, ten different types of Aluminum scraps were selected and tested including rolling mill cuttings, cast ingots, profiles, printing plates, fridge shreds, car plates, margarine foil, bottle caps, turnings and granules, as illustrated in Fig.2.

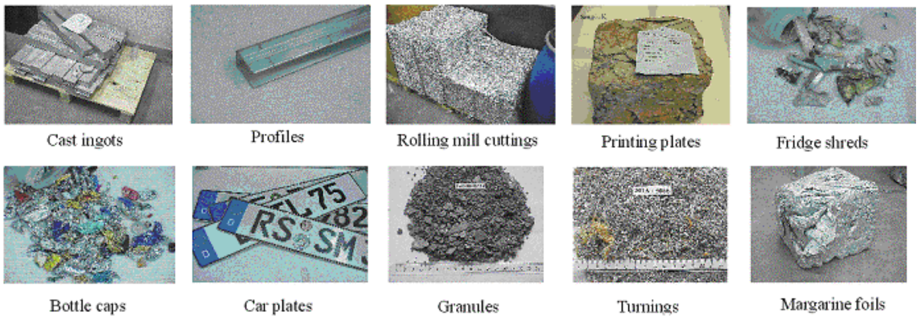


Fig. 2: Photos of the ten scraps investigated [1]

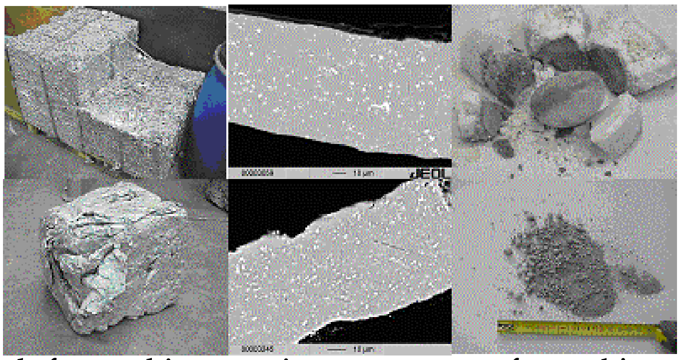
Melting experiments were carried out in a laboratory-scale electrical resistance chamber furnace with controlled nitrogen atmosphere at 800-900°C. The details of the experimental set-up were introduced in the previous publications [1,2]. The NaCl-KCl-Na_3AlF_6 system was used as salt flux in order to protect the metal against oxidation, to absorb the contaminants and to promote coalescence of Aluminum droplets. To ensure a good fluidity of the molten flux, a weight ratio of salt to scrap of two was adopted. During melting, the metal phase will usually melt first due to its lower melting point and will settle down on the bottom of the crucible. After melting, the sample was dissolved in water to recover entrained metal droplets. The recovered metal was evaluated according to the total weight and size distribution.

In addition, the melting behaviour of room temperature Aluminum cube in molten salt were investigated at 800ÚC in a vertical carbolite tube furnace with thermal gravity analysis (TGA) under nitrogen atmosphere. The Aluminum sample was placed in a stainless steel basket or screwed on a stainless steel rod. After the Aluminum sample was put into the melts, weight change due to the change of buoyancy force during the process was recorded. The scrap melting information can be obtained by the analysis of the recorded weight changing curves, and the range of the melting time of the Aluminum sample under a controlled condition can be estimated.

2.1 Melting behaviour under different conditions

In order for the salt to absorb the oxide film and the surface contaminants, the wetting ability of the salt to the scrap's oxide film must be higher than that to the molten Aluminum. Therefore, the surface tension of the salt flux and the surface condition of the scrap play a critical role in metal and salt separation, and furthermore in metal recovery. Cryolite in the salt flux plays important role in lowering the interfacial energy between oxide layers and the Aluminum melt. In addition, melting temperature and physical stirring may influence the physical properties of the salt flux and the mixing behaviour of the melt, which will be discussed with melting margarine foils as an example.

The scrap type has significant influence on the melting behaviour. As an example, Fig. 3 shows the rolling mill cuttings and the margarine foils and recovered metal beads after melting at 800ÚC for 2 hours in the salt flux (70 wt% NaCl – 30 wt% KCl with additional 5 wt% cryolite). It is clear that surface condition has a significant effect on the metal recycling. For melting of margarine foils, the recovered metal beads have a size distribution, which is influenced by the melting conditions, such as temperature, salt compositions and stirring.



before melting **microstructure** **after melting**

Fig. 3: Rolling mill cuttings and margarine foils

Fig. 4 shows the size-distribution of metal beads for margarine foils under different conditions. Increasing the temperature from 800 to 900°C alters the distribution of the metal beads. Higher temperature improves the metal agglomeration, but the effect is less substantial compared to the effect of cryolite addition. Due to the particular surface conditions of the margarine foils, the agglomeration of the metal droplets was difficult. From the present experimental study, it is obvious that higher concentration of cryolite in the salt flux gives better coalescence of the metal droplets. The addition of cryolite may promote the oxide film removing according to the Al_2O_3 – Na_3AlF_6 phase diagram [3]. However, it reduces the density difference between the salt and the metal [4], and hinders the metal separation from the salt and further the metal phase settling. Therefore, the cryolite addition should be kept to the minimum necessary for the adequate performance in the process. In addition, the effect of kinetic factor on the melting behaviour was studied. After a melting time of one hour at 800ºC, the crucible was taken out from the furnace. The molten metal and the salt slag were shortly stirred with an alumina rod, and quickly put back into the furnace for another hour of stabilising. It was found that the size of metal beads is increased with stirring. In addition, a longer melting time increases slightly the agglomeration of the metal beads.

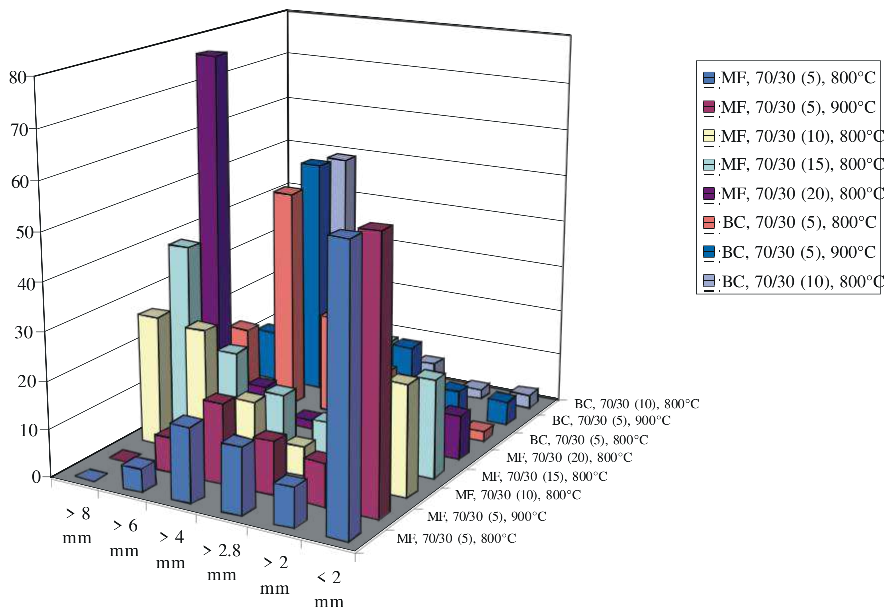


Fig. 4: Size distribution of the metal beads from melting of margarine foils (MF) and bottle caps (BC) under different experimental conditions

2.2 Assessment on recyclability

Different types of scraps have different melting behaviour, and therefore lead to varying metal yield and salt consumption. The scrap shape, size, surface conditions and organic contents have a significant impact on the melting process. The organic contaminants normally would react first during scrap heating and subsequent melting stage. Under similar conditions, the larger metal beads would coalesce more easily and settle from the flux phase to the metal phase. The scrap with a higher percentage of larger beads would be considered to have better recyclability. Therefore, the higher recyclability can be obtained by higher recoverable metal amount and higher coalescence factor.

The recoverable metal sum was calculated based on the weight of collected metal with the size larger than 1mm, divided by the weight of charged scrap. It signifies the metal content of the scrap if potential reactions of the salt flux with metal were disregarded. The coalescence factor represents the observed coalescence degree of the melted scrap. The smaller the factor, the more difficult for the metal coalescence, i.e. more small metal beads were formed. This in a way means more metal entrapped into salt, and less metal yield. Among the ten investigated scrap samples, the recyclability is ranked from high to low as follows: cast ingot, profiles, rolling mill cuttings, printing plates, fridge shreds, bottle caps, car plates, turnings, granules and margarine foil. In the case of cast ingot, profiles, rolling mill cuttings, printing plates, the metal droplets had coalesced well and settled down to form metal phase due to the less contaminants and better surface properties. Flux and metal did not separate well in the case of fridge shreds, car plates, bottle caps, margarine foil, turnings and granules.

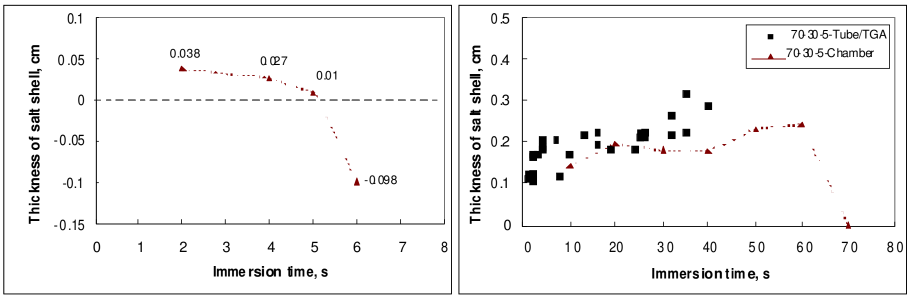
Both operating practice and the melting experiments have revealed that the scrap characteristics have a substantial influence on the metal yield. The main characteristics include: metal content, size, surface to volume ratio and contamination etc. However, for a given type of scrap, there may be differences in size like granules, shapes like turnings, or contamination extent like fridge shred. The average recoverable metal content is 68.7 wt% for melting granules with size of less than 1.4 mm, 92.0 wt% with size of larger than 6 mm. The metal phase from melting of the largest granule size was a single ball of metal with occasional small metal beads still trapped into the salt flux. The metal phase was easy to separate from the salt flux. However, separating the metal phase from the slag in the melting of the smaller granules was more difficult. The lower metal recovery for the smaller size is mainly due to the more contamination and higher surface area. The contamination is in the form of attached spent salt slag from salt reclamation plant, which has a considerable effect on the melting behaviour of the granules.

2.3 Melting scrap cube in molten salt

A series of experiments were carried out to study the melting behaviour of a room temperature Aluminum cube in molten salt and Aluminum melts. The melting rate was measured, and the influence of the salt layer on melting behaviour was investigated. It was found that the salt flux layer plays a very important role in the melting process. The formation of a salt shell retards the heat transfer to the scrap cube, and thus slows down the melting process, as shown in Fig.5.

Fig. 5: scrap cube melting in molten salt and Aluminum melts

To study the formation and re-melting of salt shell, the scrap cubes screwed on a steel rod (in the TGA tube furnace) or handled with steel basket (in a chamber furnace) were immersed into the melt and taken out after a time to identify the salt shell formed on the scrap cubes. The salt was with the composition of 70wt% NaCl -30wt% KCl plus additional 5wt% of cryolite. The salt shell formed was then weighed and its average thickness was measured. The results are shown in Fig.6 (a) and (b).



(a) in molten salt and Al melt (b) in molten salt

Fig. 6: Salt shell formed on scrap cube in molten melts

In Fig.6 (b), the squares show the thickness of salt shell formed on the scrap cube of 10 to 15 g in 120 g salt melt. The triangles show the average thickness of the shell formed on the scrap cube of 3.66 g in 250 g salt melt. The weight ratio of scrap cube to salt melt increases the shell thickness because of the cooling effect of the scrap solid. Compared with the results in Fig.6 (a) when both salt and Aluminum melts are present, the salt shell formed in molten salt is much thicker and thus the visible melting time of the scrap cube – salt shell is thus much longer.

3. Process modelling

3.1 Computational fluid-dynamics (CFD) furnace model

The complexity in a rotary melting furnace is due to the high temperature and complex chemical reactions, and particularly the complex scrap feed. Fig.7 illustrates the complex transport phenomena and interactions between the feed, products and the furnace walls.

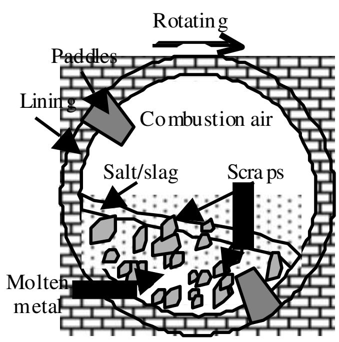


Fig. 7: Complex phenomena inside the rotary melting furnace

Modelling and optimisation of a rotary melting furnace were conducted on the basis of CFD framework [5]. User developed submodels of scrap melting and metal burn-off are coupled to the CFD process model for heat transfer calculations in the scrap – salt zone. The reconciled industrial operation data were used to estimate the relationship between the metal burn-off and the Aluminum scrap feed type for process modelling. With the coupled scrap melting sub-model, the melting rate of the Aluminum scrap and the heat sink due to melting were calculated. Simultaneously, the CFD calculations provide the sub-model with the temperature information. In addition, the sensitivity of the model parameters was tested and process optimisation was conducted based on the model calculation.

The industrial scale rotary furnace used in the CFD model is with 3.0 m in inner diameter, 3.65 m in outer diameter and 6.9 m in length. The model consists of a gas region in the upper part of the furnace (turbulent flow, combustion, and radiative heat transfer), a solid region of the furnace lining, and a solid-liquid region in the lower part of the furnace (melting of scrap in molten salt and metal). The solid-liquid region was assumed as a conducting solid and stagnant liquid. The rotation of the furnace, normally about 1.33 rpm, and the agitation of the paddles built in the furnace wall were not considered at the present stage. The governing equations for conservation of mass, momentum, and energy in a turbulent flow system of the combustion space of the rotary furnace were described elsewhere [6]. In the CFD simulation, the standard *k-e* model was applied in most of the simulations for turbulent gas combustion and flow. Eddy dissipation model [5] was used for representing the combustion of the natural gas with oxygen, which is based on the concept that chemical reaction is fast relative to the transport processes in the flow. For the scrap melting process in the rotary furnace, heat transfer from the gas zone through the gas-scrap interface is the key for the scrap melting process and radiation plays a dominant role. The discrete transfer model (DTM) was used to model the gas phase radiation. The emissivity of the furnace interior wall of 0.8 was used in most of the simulations for the process modelling.

The thermal properties of the mixture of the salt and the scrap were calculated based on the mass fraction and the phase state of the materials in the mixture, as well as the voidage in the scrap-salt zone. The initial and boundary conditions were determined based on steady-state calculations and industrial observations. The initial temperature in the gas zone and scrap-salt zone was set as 303 K and there is no fluid flow in the gas zone where the absolute pressure was set as 1 atm. The initial temperature in the lining structure was imported from a previous steady simulation of heating the empty furnace. The initial size distribution of the scrap was defined and classified into several scrap groups. The inlet of the burner was simplified to reduce the computing time. Pressure boundary condition, relatively 0 Pa, is set for the outlet. A constant effective heat transfer coefficient of 15 W/m^2K (including radiation contribution) was applied for the outside wall and the environmental temperature was set as 303 K.

3.2 Sub-model: melting of scrap in salt and metal melt

To describe scrap melting in a molten salt – metal bath, numerical modelling was conducted for a single scarp particle. The governing partial differential equations of the melting model were presented in details in the previous publication [7]. By solving these equations with a finite difference method, the melting process of a scrap sphere and the formation and re-melting of the salt shell under the defined conditions can be calculated. The calculated results were compared with the measured average thickness of the salt shell, and a reasonable agreement was obtained, as shown in Fig.8. It can be seen that the Aluminum metal inside the salt shell melts prior to the salt shell because of the higher melting point of the salt. The salt shell formation and re-melting were found to be the rate limiting step of Aluminum scrap melting. A modified version of the scrap melting model, which takes particle size distribution into account with a population balance technique, has been developed and coupled into the CFD process model.

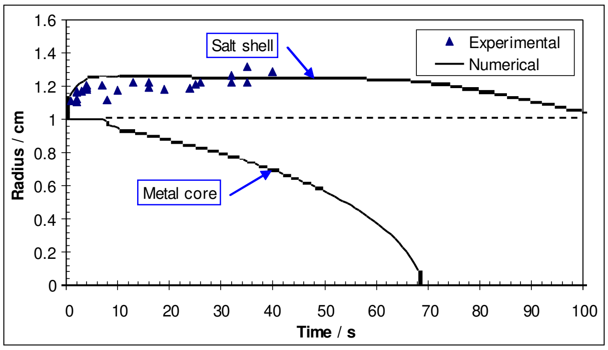


Fig. 8: Calculated and experimental results on salt shell formation and re-melting (1.0cm^3 scrap cube in a molten salt melt at 800^{o}C)

3.3 Sub-model: scrap burn-off

The oxidized Aluminum can never be reclaimed in secondary Aluminum process and contributes to the metal loss. The burn-off rate is dependent on the operation, salt amount, scrap quality and many other factors [8].The generated heat due to the oxidation of Aluminum metal amounts to a large portion of the total energy input, which includes direct oxidation with oxygen, and the reactions of Aluminum with H_2O or CO_2. Their subsequent reactions, e.g. combustion of H_2 and C with oxygen, also generate a lot of energy. In addition, the Aluminum metal can also react with the contaminants in the scrap, e.g. plastics, and these reactions can be regarded as the source of scrap burn-off as well.

To provide a reasonable heat source for the furnace model, a simple scrap burn-off sub-model was developed, which translates the burn-off enthalpy into heat sources for the CFD based process model. In this study, the burn-off rate from a number of furnace cycles was evaluated through data reconciliation for mass and energy balance. Based on different scrap feed, the scrap burn-off rate was classified as a function of metal yield. For example for the scrap feed with a metal yield of 80%, the scrap burn-off is about 2.69%, and the generated heat is about 657 MJ per ton of scrap feed. It was assumed that the generated heat from scrap burn-off contributes in both the gas region and the solid-liquid region with a varying ratio as a model parameter. The burn-off reactions were assumed to be evenly distributed in each region. The effect of burn-off on the mass balance was considered less significant and was ignored. The implementation of the burn-off energy source in the CFD model was linked to the measured off-gas temperature profile as function of time. It was generally believed that large variations of the off-gas temperature during melting operation were mainly due to the change in metal burn-off. For a typical cycle of scrap melting in the industry furnace with a feed of 13 tons of scrap and 4 tons of salt, 8540 MJ of burn-off energy is generated.

3.4 Modelling results

Turbulent fluid flow, gas combustion, radiation, and conjugated heat transfer, as well as scrap melting were simulated with the CFD based process model. The model results are presented in the following, which are based on the assumption that 80% of the scrap burn-off takes place in the gas phase and the remaining 20% in the solid – liquid zone.

Gas flow and combustion in the rotary furnace

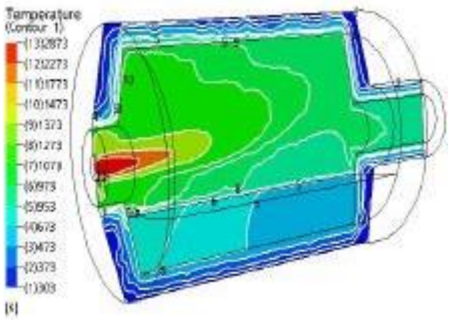


Fig. 9: Temperature field across the centre plane from the side view (x=0) in the furnace at t = 7200 s.

Natural gas combustion is the main energy source for Aluminum scrap melting in the rotary furnace. The detailed information of the fluid flow in the gas zone, the temperature distribution in the furnace and the energy flows of the process have been obtained. Fig.9 shows the temperature field in the furnace at the 7200th second, from the side view (at x=0 plane). The flame area can be clearly distinguished and its temperature is as high as 2873 K. The off-gas temperature at this moment is in the range between 1073 K and 1273 K at the furnace outlet. It also shows the temperature distribution in the scrap – salt zone and in the lining regions.

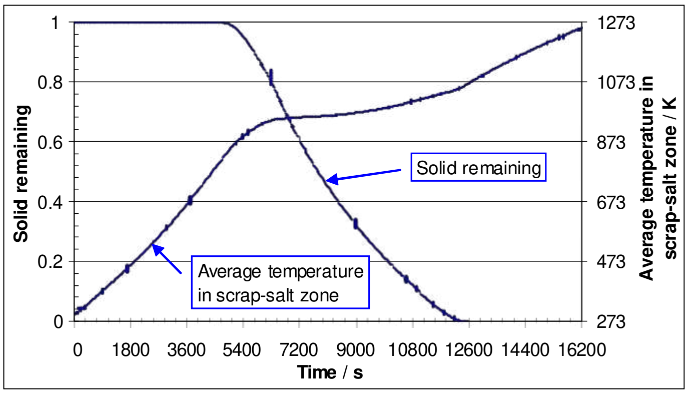


Fig. 10: Melting curve and average temperature in scrap-salt region

Scrap melting in the scrap-salt region

One of the main objectives of this study is to obtain the complete melting time under various conditions. In this case, to melt down 13 tons of Aluminum scrap and 4 tons of salt flux, the predicted total melting time is about 4 hours. Fig.10 shows the melting progress of the scrap and salt. At the beginning stage (0 s to 5400 s) and the final stage (after 10800 s), the temperature increases more rapidly, corresponding to the heating of solid and liquid. The middle part of the curve illustrates the melting stage, where the temperature in the scrap-salt region increases very slowly due to the heat sink of the partial phase change.

Energy flows and heat sources in the melting process

For the energy balance in the melting process, the main energy input consists of two parts: heat from natural gas combustion and reaction heat due to scrap burn-off. The energy input of the combustion is about 16400 MJ for a typical cycle and the burn-off heat amounts to 8540 MJ, roughly one third of the total energy input. The output of the energy is composed of the following parts: heat stored in the metal and in the salt slag, heat carried by the off-gas and leakage air, and heat loss through the furnace walls. The general energy flow is calculated and shown in Fig.11. The energy efficiency of the fuel combustion in this context is defined as the energy used for heating of the metal, and it varies between 55% and 60% on average except the first 5-6 minutes. The burn-off heat is subtracted from the calculation of the energy efficiency. The energy output carried by off-gas is about 36% on average, and the heat loss through the furnace wall is about 4% on average.

4 Summary and conclusions

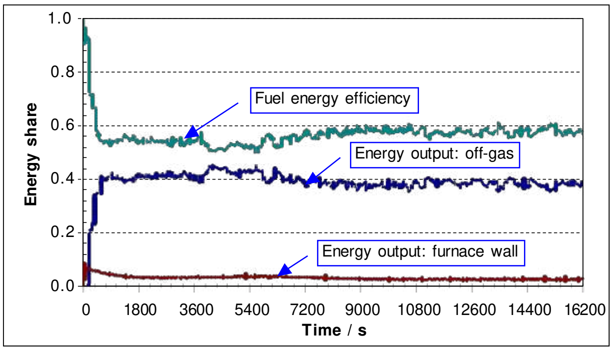


Fig. 11: Overall energy flows through inlet, outlet and furnace walls

Secondary Aluminum recovery becomes a very important part of the total Aluminum metal supply. For efficient processing of Aluminum scrap, melting rate and scrap recyclability are essential indicators for the evaluation of the Aluminum recycling, which depend on many factors. Melting experimental results reveal that scrap type, size, surface conditions and cleanness of scrap have a significant impact on the melting process. The recyclability of the ten selected scraps was assessed and is ranked as cast ingots, profiles, rolling mill cuttings, printing plates, fridge shreds, bottle caps, car plates, granules, turnings and margarine foils. Normally metal coalescence and recovery are increased with scrap size. The impact of temperature is not as significant as that of the salt composition; addition of cryolite is essential although the added amount should be kept to the minimum necessary. Stirring is helpful for metal agglomeration, which is the case in the industrial operation of the rotary furnaces. In general, types of scraps bearing higher levels of contaminants and organic materials can be expected to achieve a lower metal recovery. In industrial processes, an optimum scrap mix should be adopted to achieve the desirable metal content, and to allow the scrap melting with maximum content of contaminants without having a major impact on the metal yield.

A CFD based process model was developed for the scrap melting process in a rotary furnace, in which transient turbulent fluid flow, radiative heat transfer, and natural gas combustion were simulated. Experimental and numerical study of Aluminum scrap melting in molten melts, as well as industrial data measurements were applied to develop, support and validate the sub-models and further the process model. User developed sub-models for scrap melting and scrap burn-off were integrated into the CFD-based process model. With this model many process features can be simulated such as general flow and combustion characteristics in the gas region, heating and melting profile, energy distribution and overall balance in the scrap – salt region. The results indicate that the distributed scrap quality, represented by the particle size and burn-off rate of the scrap, is one of the important factors influencing the melting process. For the scrap with a higher burn-off rate, which normally is the scrap with a lower recyclability, the total melting time is shorter and the fuel consumption is lower. However, it is at the expense of higher metal loss, and thus lower metal yield.

References

1. Y. Xiao, M. Reuter and U. Boin, Recycling of Aluminum scraps and its environmental impact. Proceedings of 2nd International Conference on Environmental Concerns: Innovative Technologies and Management Options. Oct. 12 – 15, 2004, Xiamen, China, Vol. II, pp.1079-1088.
2. Y. Xiao, M. Reuter, P. Vonk, J. Vonken, H. Orbon, Th. Probst, and U. Boin, Experimental study on Aluminum scrap recycling. Proceedings of the Fourth International Symposium on Recycling of Metals and Engineered Materials. Eds. Stewart Jr., D.L., Daley, J.C. and Stephens, T.L., 22 – 25 October, 2000, USA, pp. 1075 – 1087.
3. E.M. Levin, H.F. McMurdie and M. K. Reser, Phase diagrams for ceramics, supplement (figures 4150-4999). Columbus: American Ceramic Society, 1975, p. 334.
4. J.Ye and Y. Sahai, Surface tension and density of molten salts based on equimolar NaCl-KCl with addition of fluorides. Materials Transactions, JIM, Vol. 37, No.2 1996, pp. 170 – 174.
5. ANSYS inc.: ANSYS-CFX 5.6 Users Manual, 2003.
6. B. Zhou, Y. Yang and M. A. Reuter, Process modelling of Aluminum scraps melting in molten salt and metal bath in a rotary furnace. Light Metals 2004. Eds. Alton T. Tabereaux. TMS Annual Meeting, March 14-18, 2004 Charlotte, North Carolina. TMS, Warrendale. p. 919-924.
7. B. Zhou, Y. Yang, and M.A. Reuter, Modeling of melting behavior of Aluminum metal in molten salt and metal bath. Yazawa International Symposium on Metallurgical and Materials Processing, San Diego, CA, USA, 2003, pp. 1249-1258.
8. V. Salet, Steady State Mass and Energy Balance Model of the Rotary Furnace: Study to Determine the Burn-off Rate of Aluminum Metal inside a Rotary Furnace, MSc Thesis, Delft University of Technology, Delft, Netherlands, 2003.

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