

Recycling of auto shredder residue

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Abstract

Currently, about 75% of end-of-life vehicle's (ELV) total weight is recycled in EU countries. The remaining 25%, which is called auto shredder residues (ASR) or auto fluff, is disposed of as landfill because of its complexity. It is a major challenge to reduce this percentage of obsolete cars. The European draft directive states that by the year 2006, only 15% of the vehicle's weight can be disposed of at landfill sites and by 2015, this will be reduced to 5%. The draft directive states that a further 10% can be incinerated. The quantities of shredder fluff are likely to increase in the coming years. This is because of the growing number of cars being scrapped, coupled with the increase in the amount of plastics used in cars. In Sweden, some current projects are focusing on recycling of ASR material. In this paper some different alternatives for using this material are reported. The hypothetical injection of ASR into a blast furnace concentrating on ASR's effect to some blast furnace (BF) parameters has been completed using a blast furnace mass balance model. As a result, in principle, ASR can be used as reducing agent in the BF process if certain conditions are met. The particle size of ASR material must be controlled to ensure optimal gasification of the material in the raceway. Regarding the chemical composition of ASR, the non-ferrous content can affect the pig iron quality, which is difficult to rectify at a later point. The most attractive recycling alternative is to use the products obtained from pyrolysis of ASR in appropriate metallurgical processes.

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1. Introduction

Currently, about 75% of ELV's total weight is recycled in EU countries. The remaining 25%, which is called auto shredder residues (ASR), is disposed of as landfill because of its complexity. It is a major challenge to reduce this percentage of obsolete cars going to landfill. The European draft directive states that by the year 2006, only 15% of the vehicle's weight can be disposed to discharge sites and by 2015, this will be reduced to 5%. The draft directive states that a further 10% can be incinerated. Many countries don't have the technology to achieve this directive [1].

In the last 20 years, automobile manufacturing has increased, reaching about 58 million units (excluding commercial vehicles) [2]. The Organization for Economic Cooperation and Development (OECD) has projected that the growth will be 32% from 1997 to 2020. The evolution of passenger car production in EU countries is shown in Fig. 1. From 1998, more than 14.5 million cars per year have been manufactured [3]. A statistical projection for Europe reveals a net increase in the number of end-of-life vehicles (ELV) from 8 million in 1996 to nearly 11 million in the year 2015 [4].

2. Recycling routes of end of life vehicle's (ELV's)

The conventional route for end-of-life vehicle recovery and recycling is determined by standard practices of metal recycling [5]. The process steps include the pretreatment or de-pollution (e.g. removal of tires, the battery, lubricants and fuel), and shredding and sorting the vehicle to recover valuable metals. These metals are recovered by using magnetic separation, and constituting about 75% of the total weight of ELV's they are recycled in iron and steelmaking processes [6]. Fig. 2 shows different recovery routes of ELV's. It shows that after shredding the ELV's, the treated fluff, which is generated from this process, can be used for energy recovery in a cement kiln, for feedstock in a blast furnace and for syngas.

3. Fluff or auto shredder residues (ASR)

The auto shredder residue or auto fluff is a fraction, which is obtained from the process of shredding cars, after recovery of iron and steel by magnetic separation. Usually, the recycling of automotive vehicles is focused on the reclamation of metals; however, other materials in the form of shredder fluff are disposed to landfills. The quantities of shredder fluff are likely to increase in the coming years. This is because of the grow-

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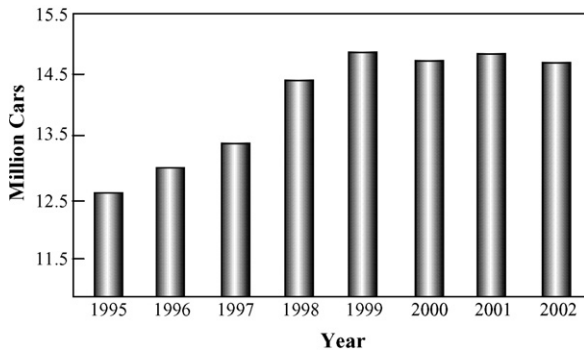


Fig. 1. Car production in EU.

ing number of cars being scrapped, coupled with the increase in the amount of plastics used in car production [2]. Currently the content of plastic is about 12% of vehicle weight [7]. About 3 Mtonnes of ASR are generated annually in North America [8]. The OECD has estimated about 2 Mtonnes of ASR per year are generated in EU countries. In Sweden, the annual flow mass of these materials is about 100,000 tonnes. This material is most often landfilled, but it is also incinerated or used as fuel in rotary kilns in cement works [9].

3.1. Characteristics of ASR

Auto shredder residue (ASR) is a solid waste, which is generated by the ferrous metal shredding industry. ASR is an extremely heterogeneous material. So to ensure a representative sample, systematic cone and quartering procedures can be employed. An typical ASR sample from a Canadian shredding operation has a density of 405 kg/m³, contains 6% moisture, 18%

of the material (>than 25.5 mm), 37% fines (<2 mm), and this material has a calorific value of 11.8 MJ/kg [10]. This material also contains metals such as zinc, lead, and copper. The most critical heavy metals are Zn and Cu at a content of 1%. The material also contains 0.25% Pb and less than 0.05% Cd and Cr. According to Quebec protocol, Zinc was found to be the most leachable at about 250 mg/l. Cd, Cu and Cr are less than 1 mg/l. However, lead is a potential problem with average concentration of 7.0 mg/l, exceeding the limit of about 5 mg/l.

Standard test leaching and toxicological analysis showed that the fluff has a low toxicity and weak mutagenity. Yet, a build-up of this material could be a future environmental problem due to, for example, the possible heavy metal accumulation from ash in the biological cycle. For this reason, a technique that makes fluff inert and exploit its heating value can be deemed appropriate.

The consumption of plastics/composites in US-built automobiles increased from 79.2 kg in 1978 to 109 kg in 1992. By 2000 the average weight of an automobile is about 1350 kg containing 135 kg of plastics. Therefore, ASR contains more plastics and less metal. Their disposal has become a more pressing issue. New technology must be developed for recycling this material [11]. Recycling is complicated because this material is very heterogeneous, density and moisture content change from site to site and from day to day as different types of source materials, automobiles and white goods, are shredded. The composition of fluff reported in Ref. [12] is shown in Fig. 3 as well as in Table 1. Fluff contains more than 40% of plastics; elastomers represent about 21%, textiles (10%), ceramic and electric materials (3%), and paint protecting coating (5%). Light and heavy fractions represent about 20.5% and 4% of the total weight of fluff [6,13].

Fluff has a higher volatile matter and ash content than coals. It starts to combust at 300 °C. This temperature is close to those

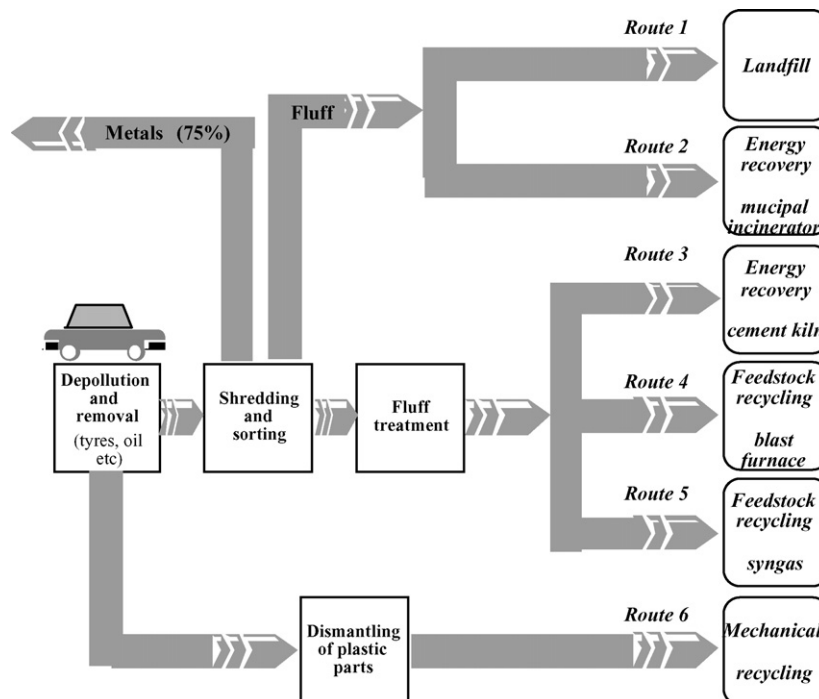


Fig. 2. Recovery routes of ELVs (Anonymous [5]).

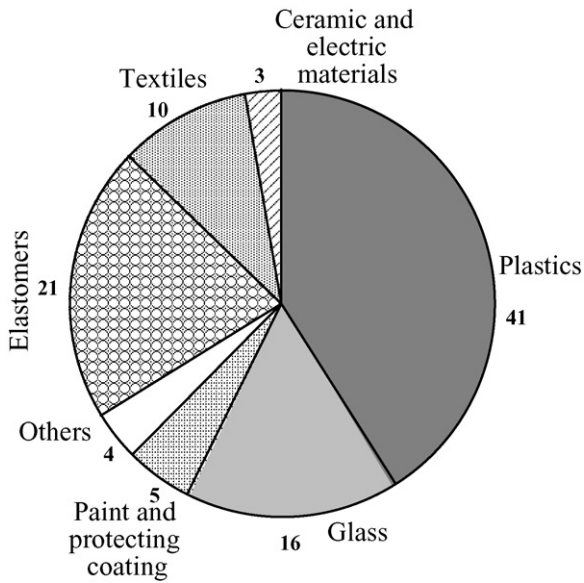


Fig. 3. Composition of fluff (Mirabile et al. [12]).

obtained from different coals, except for A (low ash) which starts at 400 °C (see Table 2). It is important to note that the maximum weight loss of fluff during combustion is obtained at 350 °C, however for other coals, the maximum weight loss is obtained between 530 and 550 °C (see Table 2).

The quantity of fluff generated in the USA is estimated to be between 2.27 and 2.72 million tonnes (e.g. 250 kg for every tonne of steel recovered by the shredder operation). This material containing 15% of plastics is deposited in landfill in the USA [14]. Some investigations on alternative methods of disposal have been ongoing. The densities of this fluff provided from North America and Europe vary from 282 to 563 kg/m³ [8]. Ash is composed of metals and inorganic materials. The moisture contents were in the range of 0.6–6.6 wt.%. The gross calorific values are between 16.9 and 30.7 MJ/kg with an average of 20.0 MJ/kg. Obviously the calorific value correlates well

with the organic content. The highest calorific value was found for the sample which contains the highest organic content [8].

4. Recycling processes for ASR

Two types of treatment of ASR are investigated, one which is oriented to material recycling and another one to energy recovery. In this paper both treatments of ASR are reviewed.

4.1. Argon process

This process is useful for sorting of plastics contained in fluff [11]. It consists of four stages for recovering plastics such as polyurethane foam (PUF), polypropylene (PP), polyvinyl chloride (PVC), and acrylonitrile butadienestyrene (ABS). Drying, physical separation, solvent extraction and solvent regeneration are the important steps for recovering these thermoplastics. Because of the potentially high water content of some ASR (40%), the drying can be energy-intensive and time consuming. Physical separation is employed in this process for separating the PUF and fines from ASR. A laboratory classification column was designed which consists of several screens and equipped with a variable output (see Fig. 4).

4.2. Pyrolysis of fluff

The process involving the reaction of water with any polymeric feed material was reported in Ref. [15]. This process is activated by an electrical input, which creates free radical species producing gasification reactions under a pressure of less than 69 KPa. The authors claim that the gases generated from this process are almost exclusively H₂, CO and CH₄. The gas produced can be used for energy fuel. The possibility of applying both pyrolysed sheet molding compound (PSMC) and pyrolysed automotive fluff (PAF) as filler in concrete was explored [16].

As stated in Ref. [17], the fast pyrolysis of ASR at atmospheric pressure between 700 and 850 °C, and with residence

Table 1
Physical and chemical characteristics of fluff [12]

C (%)	49.5	P (%)	0.7	Fe (%)	25.7
H (%)	5.3	Cr (%)	0.08	Ti (%)	0.9
O (%)	6.9	Cu (%)	1.2	H ₂ O (%)	2.2
N (%)	4.5	Zn (%)	1.9	Ash (%)	36.2
Cl (%)	0.5	Ni (%)	0.07	Volatile matter (%)	54.18
S (%)	0.2	Pb (%)	0.2	Heating value (kJ/kg)	16720
F (%)	0.05	Si (%)	2.1	Density (kg/m ³)	359

Table 2
Comparison of reactivity of fluff with different coals

Samples	Volatile matter (%)	Ash (%)	Start combustion temperature (°C)	Maximum weight loss temperature (°C)
Coal reference	24.9	10.1	310	530
A (low ash)	17.8	4.8	400	550
B (high volatile)	28.5	9.3	310	540
C (low volatile)	11.7	10.7	370	550
Fluff	54.2	36.2	300	350

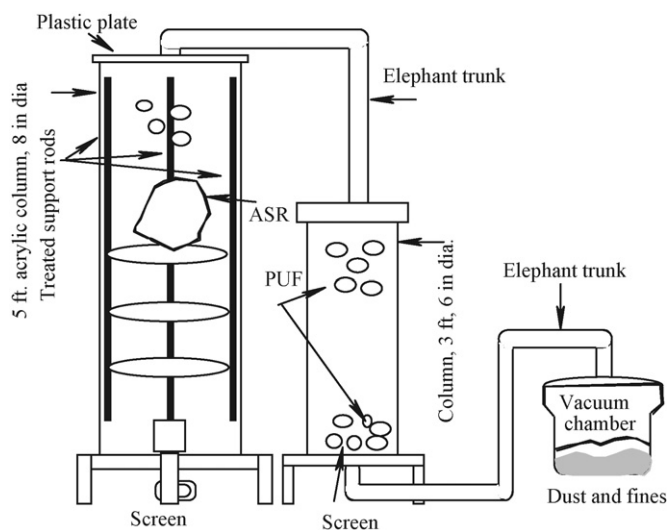


Fig. 4. Laboratory setup for physical separation of PUF, fines and plastics rich shredder fluff fractions (Bassam et al. [11]).

times between 0.3 and 1.4 s, yields the following products: Solid residue 59–68 mass%, pyrolysis gas (dry) 13–23 mass%, pyrolytic water 4–12 mass%. The five most important gases, in vol.% were CO (18–29), CO₂ (20–23), CH₄ (17–22), C₂H₄ (20–22) and C₃H₆ (1–11). It is apparent that using a high organic content ASR feed (58%) gives less solid residue and more pyrolysis gas. The pyrolysis of ASR in hot used motor oil to recover valuable oil products generates 68% of oils, 15% of non-condensable gases and 27% of non-liquefiable solid residues [18,19].

The pyrolysis of Italian ASR was investigated using thermogravimetric analysis, FT-IR and a system thermal diagnostic study (STDS) [20]. The authors have estimated the heating value of Italian ASR to be 28.3 MJ/kg (in the range of a common coal). The authors found high deviations of chlorine content (from 3 to 10 wt.%) also verified by other researchers having found a variation from 0.7 to 16.9% with an average value of 3.4%. The high gas evolution rates at low temperature suggest a good reactivity for ASR. The most important products are saturated hydrocarbon compounds (60 wt.%). Furthermore HCl, nitrogen-derived substances and oxygen-containing gases (CO, CO₂ and SO₂) are produced. These authors claim that ASR is good candidate for incineration to recover energy.

4.2.1. Microwave technology

Two new technologies for treating fluff show the potential for reducing costs and providing an environmentally conscious alternative for fluff disposal. Microwave and plasma-arc thermal destruction processes can be used for treating fluff [20,21]. The microwave process is a pyrolysis reaction that occurs at the molecular level. This process is the chemical decomposition of a substance by heat (275–300 °C). The fluff is fed to the process through a system of feed locks. The material is purged with nitrogen to prevent the combustion of carbon. Then a vapor stream is produced and subsequently condensed, after which the water is removed from the condensate. The fuel-oil obtained is sent to a storage tank. In the bottoms, carbon black is removed

at 300 °C and is cooled to 50 °C. The product obtained is passed through a magnet, then the non-magnetic fraction is crushed to fine particles to make a uniform mixture. The carbon black is obtained by screening the fine mixture material. It is claimed that no toxins such as dioxins were generated from this process. In the USA one pilot plant was tested for this process.

4.2.2. Vacuum pyrolysis of ASR

Different samples of fluff generated from European and American companies were tested in a pilot plant facility. The pyrolysis runs were carried out at temperatures between 496 and 524 °C and under total pressures of 1.2–4.7 kPa. The gas and vapor were removed and cooled down in two condensers set in series for analysis. Results show that vacuum pyrolysis appears to be an interesting process for ASR treatment compared with landfill and incineration. This process may reduce the volume of materials destined to landfills by transforming the organic substances into a valuable product [8]. Therefore, the valuable ferrous and non-ferrous metals can be separated from the residue. This process generates about 52.5% of solid residue, 27.7% of organic liquids, 13.2% of water and 6.6% of gas.

4.2.3. Comparison between Screw kiln pyrolysis process and ultrapyrolysis

ASR was pyrolysed by using a laboratory scale screw kilns (100 g/h) between 500 and 750 °C [21]. This process produces solid, liquid and gas fractions. The solid residue was the major product of the pyrolysis process and depends upon the pyrolysis temperature. A greater degradation of the organic fraction in ASR was observed at high pyrolysis temperatures and lowered the yield of solid residue. The ultra-pyrolysis process yielded about 10% less solid residue than what was obtained from the screw kiln process. Fig. 5 shows the behavior of gas and liquid in the pyrolysis process of ASR. It can be seen that the pyrolysis gas increases from 8% at 500 °C to about 20% at 750 °C. Same observation was made in ultrapyrolysis. The liquid products generated from the screw kiln process appear to be highest at lower temperatures and then decreases as the pyrolysis increases. This

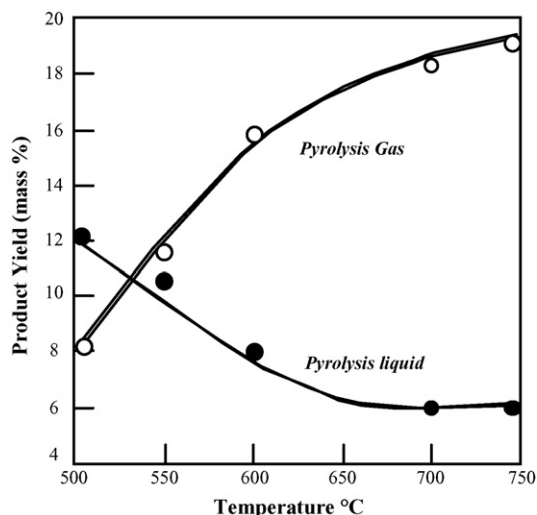


Fig. 5. Behavior of gas and liquid in ASR pyrolysis.

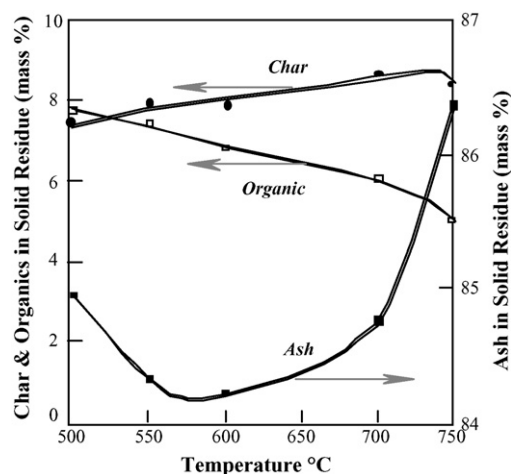


Fig. 6. Behavior of char, organic and ash.

is because the chain scission reactions occur at high temperature generating a gas product with low molecular weight.

4.2.4. The solid residue composition in the pyrolysis process

The solid residues in the pyrolysis process are composed of three substances: organic, carbonaceous char and inorganic ash. Their behavior as a function of pyrolysis temperatures is presented in Fig. 6. It can be seen that the organic fraction decreases while the inorganic content increases as the pyrolysis temperature increases. However, the carbonaceous char is constant (between 7% and 9%) [21].

4.2.5. The liquid composition in the pyrolysis process

About 15 major compounds were detected in pyrolysis at 500 °C. These compounds are: benzene, toluene, 1-pentene, ethylbenzene, styrene, 1-hexene, 2-butanone, 1-propene, 2-methyl, 1,3-pentadiene, cyclopropane, 1, 2-dimethyl, *cis*-, cyclopentene, 1-methyl-, *p*-xylene, 1-heptene, 1-octene, 1,3-cyclopentadiene [21].

4.2.6. The gas composition in the pyrolysis process

Hydrogen, CO, CO₂ and low molecular weight hydrocarbons are the major chemical substances present in the pyrolysis gas. Hydrogen is constant between 500 and 750 °C, however, at high temperatures; C₃ Hydrocarbons show a noticeable decrease while CO and CH₄ continue to increase. The maximum quantities of C₂H₄ and methane are obtained at 750 °C. C₂H₆ and C₃H₆ occur at a lower temperature, about 600 °C [21].

4.2.7. Comparison between conventional pyrolysis and fast pyrolysis

Both conventional and fast pyrolysis (CP, FP) processes offer an attractive way for the recovery of energy from ASR as an alternative to more traditional routes. In both cases, carbon conversion to gaseous and liquid products was more than 80% for temperatures ranging from 500 to 800 °C [22]. The char yield decreases in the temperature range 500–800 °C from 55% to 40% considering CP. However, in the case of FP, the char yield

is lower. It decreases from 48% to 25%. The tar yield for CP increases from 35% to 58%, and in the case of FP, this product decreases from 25% to 20%. The gas yield increases for CP, however for FP, this product increases only slightly from 5% to 10%. It should be noted that, the higher heating values (HHV) of CP gas ranged from 8.8 to 25.07 MJ/N m³. The FP oil HHVs ranged between 28.8 and 36.27 MJ/kg.

4.2.8. Catalytic pyrolysis of ASR

This approach was developed at Argon national laboratory in the USA [23]. A synthetic ASR made up from pure materials was pyrolysed in a ceramic tube reactor inserted into the 30-cm heating zone of an electric furnace. The catalytic pyrolysis of synthetic ASR was performed in the presence of several oxides such as: MgO–ZnO, ZnO–TiO₂, TiO₂–SiO₂, MgZrO₃, MgTiO₃, Fe₃O₄, CuO, Montmorillonite K10, ASR char, and ZnO–Al₂O₃. The liquids are collected in a series of three condensers, the first water-cooled, the others cooled by glycol at –20 °C and are examined by GC/MS. The gas mixtures are further analyzed by FT-IR. Usually, the uncatalyzed reactions of the synthetic ASR generate between 6% and 9% of CO₂. In the presence of Fe₃O₄ and oxidation of carbon by the metal oxide, the reaction generates about 18% of CO₂. The role of catalysis is to lower the decomposition temperature by lowering the activation energy [23].

4.2.9. Kanemura plant (Japan)

This plant treats about 90 tonnes/day of ASR. The process consists of pyrolysis drum, combustion chamber/boiler, electric precipitator, bag filter and residue separation system. The power generated at this plant is about 2000 kW, and the operation was started in May 1998. The pyrolysis gas is used in electric power, after passing through a combustion chamber/boiler. The pyrolysis residue is sorted into metal and char fractions. The metal is recycled and char is used in the combustion chamber/boiler for electric power [24].

4.3. Injection of ASR into blast furnace

4.3.1. Literature survey

The blast furnace process has already provided proof that it can be ecologically and economically sensible to recycle beneficiated residual materials with sufficient energetic potential [25]. ASR can in principle be injected into a blast furnace as an auxiliary reductant but certain parameters must be considered. These parameters include: physical properties of ASR, energy content and chemical composition of ASR, non ferrous elements contained in ASR, and the amount of ASR needed to maintain a continuous supply to a blast furnace. This material was tested in a pilot plant [12], and it was claimed that the temperature and atmosphere conditions characterizing normal blast furnace operation allow the complete destruction of organic compounds and avoid the formation of dioxins. Furthermore, heavy metals are dissolved in the hot metal and in the slag. During the production of hot metal in blast furnaces, certain elements that either have a detrimental affect on the operation or that dissolve in the hot metal are unavoidably charged to the process as impuri-

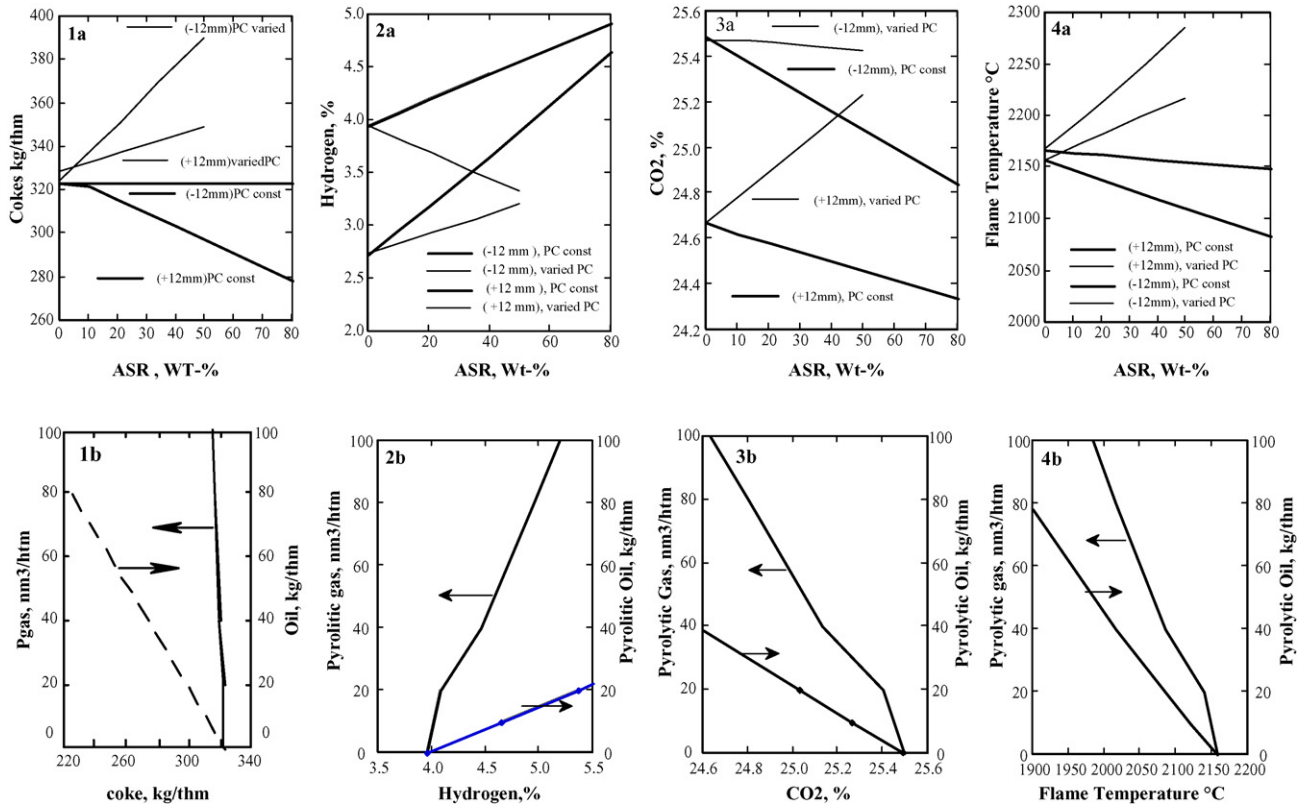


Fig. 7. Effect of by-products injected on blast furnace parameters: (a) fluff (± 12 mm) and (b) gas and oil from ASR pyrolysis.

ties in iron ore burden, the reducing agents, and other additives. The trend of current net value (CNV) towards fluff rate injection for 3, 5, and 12 working years have a positive value in the range 390–950 kg/h of injected fluff with a maximum value, corresponding to 750 kg/h. This represents about 2% of the blast furnace auxiliary fuel.

In the case of an injected quantity higher than 750 kg/h, the CNV decreases due to the higher operating costs necessary for maintaining adiabatic temperature combustion (ATC) in the fixed range (oxygen and coke consumption). Using thermal valorization to treat this amount of fluff, the CNV at 10 years varies between € 3,800,000 and 6,000,000 (approximately three to six times the investment cost) with a return of investment of about 1 year [12].

A new recycling process of ASR called Thermo-bath process was reported in Ref. [26]. This process has been developed by using coal tar based oil. ASR is separated to floats (plastics) and sediments (metals, glass and sand) by specific gravity differences. The produced plastics can be used as reducing agent by injection into a blast furnace. The metals remaining can be used in the steel-making process. It was estimated about 96% of ELVs can be recycled by this new process combined with the iron-making process.

4.3.2. Modeling case study

This work has been performed as part of the recycling program in MiMeR (Minerals and Metals Recycling center) at Luleå University [27]. The aim of the project is the utilization of ASR in the blast furnace as reducing agent. The SSAB (Swedish iron

and steel maker) Blast furnace model was used for the calculations. The chemical composition of the materials provided by a Swedish auto shredder company (two fractions of ASR, gas and oil generated from ASR microwave pyrolysis) was injected in the model. The main objective of this work is to evaluate different parameters set up in the SSAB blast furnace during injection of different by-products generated from the auto shredder. The results are shown in Fig. 7. Two case studies were considered in the calculation:

1. Injection of different amounts of by-products with fixed amount of pulverized coal (PC).
2. Injection of different amount of by-products with varied amount of pulverized coal (PC).

4.3.2.1. Injection of fluff +12 mm. Fig. 7(a) shows the effect of injection of two ASR fractions on different parameters set up in the blast furnace, such as coke amount, hydrogen generation, CO₂ generation and flame temperature in the raceway. The effect of ASR injection on the coke amount is shown in Fig. 7(1a). With increasing amount of ASR in the PCI, the amount of coke is decreasing in the first case. Using about 40% of ASR in PCI can save 10 kg/thm of coke. However, in the second case, the coke amount is increasing. Furthermore, the slag amount is slightly increasing with increasing ASR in PCI for both cases. Hydrogen generation is increasing with increasing ASR in both cases (see Fig. 7(2a)). This is because this particular ASR contains a high amount of organic compounds. In the first case, the CO₂

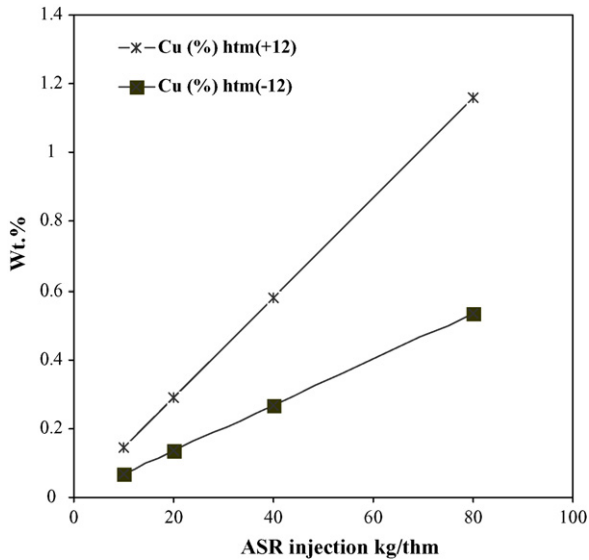


Fig. 8. Evolution of copper in hot metal as function of fluff and rest product injection.

emission is reduced with increasing ASR injection due to the hydrogen content in ASR reducing iron oxides in place of CO. However, CO₂ generation is increasing in the second case where the ASR amount is low. The flame temperature (FT) in the raceway is dropped about 40 °C in the first case; in the second case, it is increased with increasing content of ASR in PCI. If 40% ASR is injected, the FT will increase about 100 °C (see Fig. 7(4a)). It is important to note that no effect was obtained on basicity and slag formation.

4.3.2.2. *Injection of rest product –12 mm.* When the amount of rest product is varied in the injection and the pulverized coal is constant, the coke rate is stable. However, in the second case, when 50% of the injected material is rest product and PCI is varied, the amount of coke will increase from 325 to 390 kg/thm (see Fig. 7(1a)). When using the rest product in the blast furnace for both cases, the slag formation will increase. By using 35% injection of this material, the amount of slag is increased by

30 kg/thm in the first case, and by 18 kg/thm in the second case. The basicity and subsequently the pellets charge in the blast furnace will slightly decrease but this does not depend on the behavior of injection material. CO₂ emission is decreasing with increasing rest product in the injection material when the amount of PC is kept constant (see Fig. 7(3a)). As reported in this figure, this emission is stable when the amounts of PC and rest product are varied.

4.3.2.3. *Injection of pyrolytic gas.* The same methodology used for the different fractions of ASR was applied for pyrolytic gas injection into the blast furnace. Basically, the calculation is focused on the evaluation of the effect of pyrolytic gas injection into a BF on different parameters such as hydrogen generation, CO₂ generation, flame temperature, coke rate as well as slag formation and basicity. The results are shown in Fig. 7(b). The coke rate became stable when the gas injection with a fixed amount of PC is introduced (see Fig. 7(1b)). Injection of 100 nm³/thm of gas with a fixed amount of PC decreases CO₂ generation by about 1%. On the other hand, CO₂ decreases about 0.5% under the same conditions when pyrolytic gas is injected with varying amounts of PC, see Fig. 7(3b), flame temperature is decreased as well (Fig. 7(4b)). If 100 nm³/thm of gas is injected with 40 kg/thm of PC, the coke rate is increased about 70 kg/thm and the flame temperature is decreased by about 150 °C.

4.3.2.4. *Injection of pyrolytic oil.* The chemical analysis of an oil fraction obtained from microwave pyrolysis of ASR is injected into the SSAB model. The calculation was made considering the two cases used for previous calculations. The same parameters evaluated earlier in the BF model are evaluated now. Fig. 7b summarizes the results obtained. In general, the basicity of slag is stable in both cases, the CO₂ emission is decreasing (Fig. 7(3b)). It is important to note that the amount of slag is decreased by 100 kg/thm when 35% oil injection is used with a fixed amount of PC. Slag amount decreases by 20 kg/thm in the second case. The flame temperature is decreased by 250 °C as well, The flame temperature decreases by only 100 °C, if we

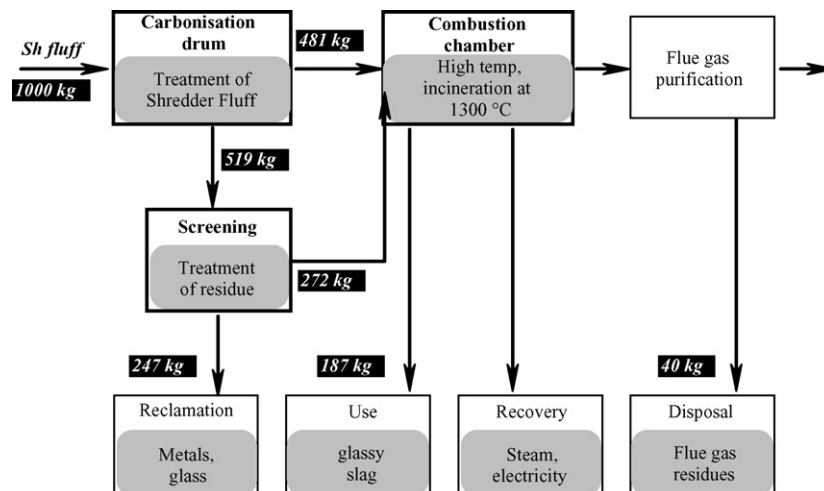


Fig. 9. Material stream of shredder fluff treatment [7].

inject 35% of oil with varied PC injection. No significant change was obtained on slag formation and pellets rate.

Fig. 8 shows the evolution of copper content in hot metal as a function of fluff and rest product injection. From this figure, it can be seen that with an increasing amount of both products in PCI, the copper is increasing in hot metal. However, copper in hot metal increases more with fluff injection because fluff contains more copper than rest product. Controlling this element is very important to produce high quality of hot metal.

5. Thermal treatment of ASR

Thermal treatment of shredder fluff (SF), shown in Fig. 9, is capable of destroying the contained organic constituents at 1300 °C [7]. Therefore, their volume is reduced to a minimum and only the flue gas purification products need to be treated as hazardous waste. The thermal treatment of approximately 1.2 million m³ of SF, yields about 97,000 m³ of glassy slag plus 66,000 m³ of metals plus 15,000 m³ of flue gas purification products. On the other hand, mineralization of this material yields a glassy slag, and residual metals are separated and returned to the materials cycle [7].

5.1. Fluidized-bed combustion

Auto fluff can be combusted successfully in a conventional fluidized-bed combustor between 677 and 866 °C, with carbon combustion efficiency in the range of 75.2–89.2% [28]. In this process, the effects of fractional excess air, fluidizing air velocity, bed temperature and the feed rate play important roles in combustion. The authors confirm that the combustion of this material by itself is possible when the provided combustion air is preheated adequately to around 777 °C.

5.2. Citron's solution for ASR

The plant was located in the harbor area of Le Havre (France). More than 10,000 tonnes of ASR were recycled in this plant.

A new thermal recycling process (Oxy-reducer process) was developed to recover the metals while the organic components are used for their calorific content and their reducing potential [29]. This process is undertaken by a rotating furnace. It consists of: heating and pyrolysis of the organic compounds, reduction of metallic oxides to their metallic states, and their separation from Fe, Cu and Mn fractions at high temperature and the oxidation of the process gases. This process is controlled by temperature, concentration of oxygen and retention time. Forty-five percent of the ASR is recycled as material, and 50% recycled as calorific substitute for natural gas. Based on Citron's experience, the most important cost drivers for this process are the size of the plant, location process temperature and process development costs. The schematic of this process is shown in Fig. 10.

6. Other utilization of ASR

6.1. Using ASR as a binder in asphalt

Automotive shredder residue (ASR) can be used in asphalt as a binder, an aggregate, and both a binder and an aggregate [30]. The authors studied compatibility between ASR and asphalt by differential scanning calorimeter, polarized light microscopy, and visual compatibility testing. They also investigated the viscous and elastic behavior of binders by dynamic shear rheometer and aging susceptibility by recording infrared spectra (FT-IR). The authors conclude that there are certain advantages to use ASR as an asphalt modifier, such as a reduction of the oxidation of asphalt and longer elastic memory, preventing fatigue cracking.

6.2. Utilization of ASR as filler in concrete

The residue obtained from pyrolysis of ASR can be employed as filler in concrete, asphalt and in plastics [16,30–32], because the finest fraction of this material (<250 μm) contains minerals, metals and organics. The large occurrence of fibers present

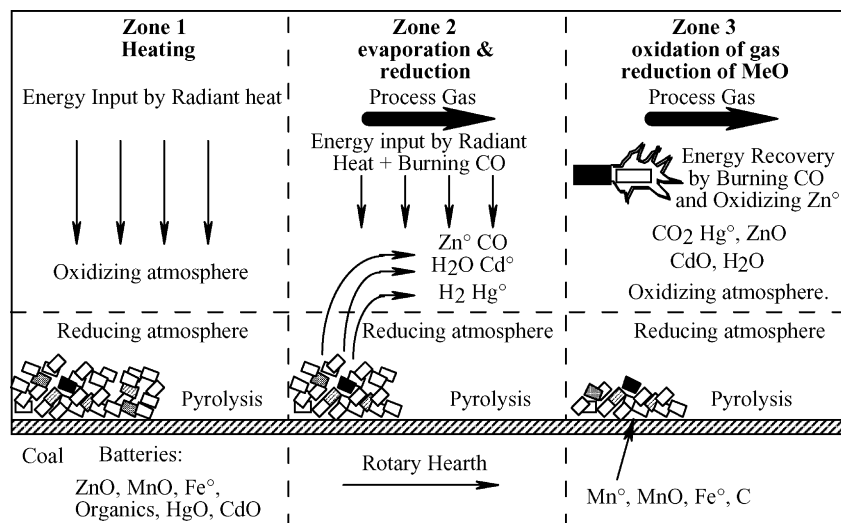


Fig. 10. Oxyreducer™ technology.

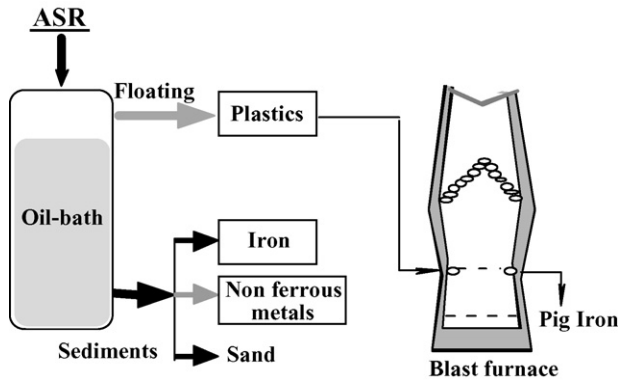


Fig. 11. ASR recycling with thermo-bath process.

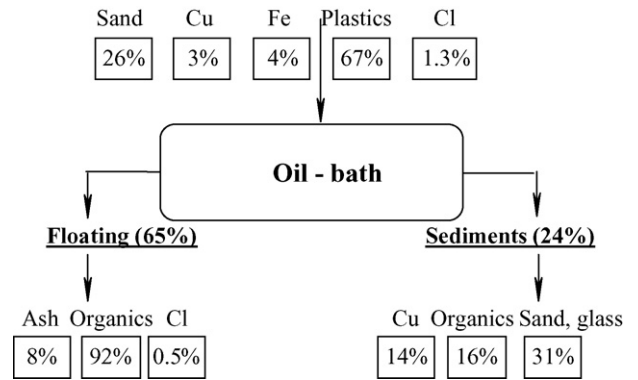


Fig. 12. Material balance in pilot plant.

in this fraction was observed using SEM. These fibers could offer interesting properties in the case of valorization as a filler substitute.

6.3. Utilization of ASR in composite applications

Rigid composites were prepared from ASR using isocyanate-based binders [33]. After examining their past findings, the authors presented preliminary results of their new research into rigid ASR composites. Strength properties were evaluated for composites prepared from various types of ASR and different binder systems.

6.4. Thermo-bath process for recycling ASR

This process was developed by Japanese researchers [34]. It consists of heating ASR in an oil bath using coal tar based oil, a by-product from steel works as a heat medium. ASR is heated quickly in the oil bath at 280 °C, and by gravity, the organic plastic is easily separated, which floats and inorganic metal sediments. The floating plastics can be fed into blast furnaces as a reducing agent and the metal can be recycled (see Fig. 11).

From this investigation, a pilot plant has been built in Japan where experiments were conducted concerning ASR recycling by Thermo-bath process. The material balance obtained from the experiment is given in Fig. 11 showing that ASR is easily separated into floating material and sediments within a time of 20 min. From oil bath separation, they obtain about 65% of material in floating and 24% in sediments. On the other hand, Fig. 12 shows that the floating part contains 92% of organic, 8% ash and 0.5% Cl₂. The sediment part contains 16% of organic, 39% iron 14% Cu, and 31% of sand and glass. According to [34] in regard to EU directive, 95% of an ELV must be recycled of which a maximum of 10% for energy recovery in 2005, consequently a total ELV recycling ratio of 96% can be achieved by this method.

6.5. TwinRec

This process was developed by Japanese researchers in 1995 and was designed to treat shredding residues, swage sludge, fly ash waste plastics, liquid medical waste and municipal solid

waste [35]. It consists of two systems: A fluidized bed gasifier (500–600 °C), which can separate the combustible portion and the dust from the inert and metallic particles of shredder dust. Then fuel gas and carbonaceous particles generated from the first system are burnt together in a cyclonic combustion chamber at 1350–1450 °C by addition of secondary air. Ando et al., 2002 claim that by using the TwinRec process, from a 25% feed of ASR, 10% can be recycled, 12.5% used as energy recovery and 2.5% landfill.

7. Conclusions

The injection of plastics into the blast furnace is not only technically feasible but also highly profitable. Waste plastics have been tested for their suitability as reducing agents in the blast furnace as a substitute for coal or oil. Two companies, Stahlwerke Bremen in Germany and NKK (Nihon Kokan Kabushiki Kaisha) in Japan, have injected waste plastics in their blast furnaces. The substitution of plastics may minimize CO₂, NO_x and SO_x emissions and save about 40% of energy.

Auto fluff or auto shredder residue is a fraction obtained from shredding of end-of-life of vehicles. This fraction is heterogeneous. It has a heat value similar to those reducing agents used in iron and steel-making processes, high density and volatile matter in fluff also contains high contents of heavy metals such as Cu, and Zn. The volume of fluff represents <0.3% of overall EU waste.

Several techniques have been investigated to handle ASR. Landfill is one option, however, as European regulations become stricter it is better to choose other recovery routes such as energy recovery in incinerators, blast furnaces, and cement kilns. This option is also regulated by EU directive, where 10% is the maximum percentage of fluff to use for energy recovery. Fluff can be used as material recycling such as reducing agents in the blast furnace, EAF process, cupola furnace or oxy-fine technique. The fluff energy recovered by injection into a blast furnace in the limits highlighted above can be assessed as promising. Fluff can be used as binders or fillers in asphalt and concrete. But for this option, a pretreatment of fluff is needed.

The chemical analyses of four different products provided from a Swedish company were injected into the SSAB model based on the heat and mass balance of a blast furnace. The results

of the calculations show no significant change in the parameters set up by SSAB for their blast furnace, when these products were injected. One problem that appears is the non-ferrous content in the fluff and rest product. The content of these compounds is limited to ensure pig iron quality. As SSAB is sensitive for the quality of their product, the two fractions of ASR used in this simulation cannot be used in the real process as it is. The material needs more refining by others methods. The injection of pyrolytic gas and oil into the blast furnace is possible. However, more attention should be shown to the CO/CO₂ content in the gases obtained from microwave pyrolysis.

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