EXECUTIVE SUMMARY

It is well established that end-of-life products such as vehicles, white goods or mixed scrap undergo a shredding process. It consists of a heavy hammer mill comminuting the waste and is equipped with a subsequent sorting step separating a heavy and a light fraction. Whereas the heavy fraction predominantly consists of metals which can be recycled for the so called shredder light fraction (SLF) up to now no adequate solution is available. SLF contains lot of plastics as well as fine inorganic materials (e.g. glass, sand, dust, rust). Also other organic compounds and metals are present in varying portions.

The directive 53/2000/EC on end-of-life vehicles demands considerable high quotas for recycling and recovery. Since in 2015 the directive will be further tightened significant improvements to raise the recycling rate are necessary. By applying mechanical processes, the SLF can be separated into plastics, fines and fluff. For the plastics several possibilities for recycling already exist (e.g. reduction agent for the blast furnace process). The fines, also called sand or inert fraction, mainly consist of minerals and show a quite low content of organic carbon and can, thus, be landfilled. There is, however, a potential for the improving the recycling rate of the fluff fraction.

Since fluff contains a significant portion of fibers it seems worth to think about a further utilization of the material. On the one hand fibers exhibit specific properties such as high surface at low mass and are, thus, frequently used as viscosity modifier or reinforcement agent for several construction materials. On the other hand fiber handling and processing is difficult due to an entangling. Only recently a new concept for a reutilization of fluff from SLF exclusively based on mechanical processes has been presented. The product can be used for a variety of construction materials and substitute well established products based on fibers from new materials. It is, thus, clear that a recycling of SLF fluff shows significant benefits from an economical as well as from an ecological point of view.
INTRODUCTION

In the European Union numerous regulations for waste exist aiming to ensure environmentally sound practices and to avoid landfill. The directive 2008/98/EC (Anonymous 2008) introduces a waste hierarchy stipulating a priority order in waste prevention and management legislation policy. The highest priority shows waste prevention followed by preparing for re-use, recycling and other recovery methods. Disposal is the least favorable waste treatment and must be avoided whenever possible. However, in addition end-of-life vehicle treatment is in particularly driven by the directive 53/2000/EC (Anonymous, 2000). According to this directive the following quotas have to be introduces in the countries of the European Union:

- Since 2006 for all end-of life vehicles, the reuse and recovery must exceed 85 % by an average weight per vehicle and year whereas reuse and recycling must exceed 80 % by an average weight per vehicle and year.
- No later than 1st January 2015, for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95 % by an average weight per vehicle and year. Within the same time limit, the re-use and recycling shall be increased to a minimum of 85 % by an average weight per vehicle and year.

In order to comply with the quotas of directive 53/2000/EC (Anonymous, 2000) further improvements are necessary to bring about economically viable solutions.

TREATMENT OF END-OF-LIFE VEHICLES: STATE-OF-THE-ART

Passenger vehicles are extremely complex products and roughly contain about 10,000 parts consisting of approximately 40 materials (Gruden, 2008). Table 1 shows typical portions of the main material groups.

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount [mass %]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel and iron metals</td>
<td>58 – 70</td>
</tr>
<tr>
<td>Light metals (Al, Mg)</td>
<td>3 – 8</td>
</tr>
<tr>
<td>Plastics</td>
<td>8 - 18</td>
</tr>
<tr>
<td>Rubber</td>
<td>3 – 5</td>
</tr>
<tr>
<td>Glass</td>
<td>3 – 4</td>
</tr>
<tr>
<td>Operating liquids</td>
<td>2 – 5</td>
</tr>
<tr>
<td>Others</td>
<td>5 - 11</td>
</tr>
</tbody>
</table>

In Europe it is already well established today that end-of-life vehicles are collected and dismantled. In a first step a so called drainage of the vehicle is compulsory which means that all operating liquids have to be removed. Commonly the following liquids are correctly sorted (Gruden, 2008):

- Fuel (gasoline or Diesel)
- Oils (engine, gear box, differential gear unit)
- Cooling liquids (mainly water, 20 – 40 % ethylene glycol, 2 – 4 % corrosion additives)
- Hydraulic fluids (brakes, steering)
- Refrigerants (old vehicles still contain CFC)
- Windshield wiper fluid
The directive 53/2000/EC (Anonymous, 2000) further demands to remove certain components. Economically viable dismantling is, however, only possible to a certain extent. Although in the literature certain automations are described (Staake et al., 1998, Ahlmann et al., 1988, Hauesler et al., 1991, Oberlaender, 1991, Schaetzing et al., 1992, Salzmann, 1996, Sattler, 1993), labor work is still predominating resulting in high dismantling costs (Salzmann, 1996). The following components are commonly dismantled (Gruden, 2008):

- Starter batteries; for lead accumulators the directive (Anonymous, 2006a) is in force.
- Liquid storage tanks; mainly made of plastics, contaminated with fuel.
- Pyrotechnical propellants (airbags, belt pretensioners).
- Catalytic converters; due to high prices for Pt and Rh recycling is highly economically.
- Tires; contribute 3 – 5 % to total vehicle weight.
- Metallic components containing Cu, Al and Mg (cooler, heater, air conditioning systems); high metal price makes recycling economically.
- Wiring harness (up to 50 kg per vehicle); recycling of copper; Cu would result in undesired impurities of steel.
- Large plastics components (up to 150 types of plastics and up to 2,000 plastic components per vehicle); disassembling is expensive; plastics recycling only possible to a limited extent.
- Glass; laminated safety glass is difficult to recycle.

After the drainage and removal of the above mentioned parts, the vehicles undergo a series of mechanical and physical separations in order to recover the ferrous and non-ferrous metals. Typically an aggregate called shredder is used. It is a large hammer mill and comminutes the vehicles to particles as big as a fist. Downstream the shredder a wind sifting unit for separation of light fraction purifies the heavy fraction.

The heavy fraction, which accounts for about 75 % of the input material, predominately contains metals and is further separated into a ferrous and a non-ferrous part. Both streams can be economically recycled. However, the shredder light fraction which represents about 20 – 25 % of the end-of-life vehicle's weight is not feasible for a recycling schedule.

In Germany during 2006, only 16 % out of 3 million end-of-life passenger vehicles were dismantled. Out of the same three million 17 % were exported. The whereabouts of the major portion (⅔) is unknown (Berninger, 2008) but a proper disposal is unlikely. Generally, the portion end-of-life vehicles that are either legally exported or properly disposed is rather low in many EU countries, the lowest value (13 %) is reported for Poland (Scherhaufer et al., 2008).

**PROCESSING OF SHREDDER LIGHT FRACTION**

The composition of SLF is not constant. Shredder companies do not exclusively process end-of-life vehicles but also white goods, mixed scrap and other types of waste. The portion of end-of-life vehicles ranges between 27 to 85 % (Reinhardt et al., 2004) and also the composition of passenger cars is changing. Vehicles constructed in the period 1960 to 1975 contained about 78 % steel and 2.3 % fibers. During the period 1996 to 2000, however, the iron fraction was reduced to about 58 % while the fiber portion increased to 7.3 % (Reinhardt et al., 2004). In addition, the processing conditions of the shredder aggregate
can be altered. This influences the composition of SLF, in particular the metal content. In conclusion, SLF consists of the following compounds whose percentages can significantly vary:

- Plastics (thermoplastics, duroplasts, elastomeres); predominantly in form of bulk but also fibers, films and foams;
- Other organic compounds (wood, paper, lacquer residues, etc.);
- Metals (iron, copper, aluminum);
- Minerals (glass, ceramics);
- Others (sand, dust, rust, lead, zinc, etc.);

There are two main categories for the processing of SLF, so called post shredder technology. The first one uses mechanical processes based on grinding and sorting of SLF into different fractions that can, at least partially, be recycled and sold. The second category applies a thermal treatment to the SLF. The waste used in this process acts as a feedstock for energy generation and material recovery.

Among the classical thermal processes are pyrolysis, gasification and incineration. Several companies developed new industrial processes based on these classical methods optimized for SLF. These methods can be classified either as disposal or recovery (Anonymous, 2008) which is an important aspect in regard of the directive 2000/53/EC. Generally, thermal processes require a great effort (high temperatures, efficient gas cleaning, etc.) and disposal costs can be rather high. The most important industrial thermal processes are briefly introduced below.

- **Incineration**
  SLF is fired either together with municipal waste in incineration plants or in industrial processes such as the cement industry in order to recover thermal energy. This praxis is rather costly and due to heavy metal problems the maximum portion is restricted (e.g. in Switzerland maximum at 5%). Disposal costs range between 150 and 240 €/t.

- **TwinRec process**
  TwinRec technology was developed by Japanese company EBARA. It is based on a fluidized bed gasification with ash vitrification (Hirayama et al., 1995, Fujimura et al., 1997, Selinger et al., 2003). About 52% of the input stream is used for energy recovery. The main output streams are glass granulate (approx. 25%), metals (approx. 8%) and ashes (approx. 15%). About 20 lines are in operation exclusively in Japan. The cost for this process is estimated to be in the range of 120 to 200 €/t.

- **RESHMENT process**
  The Reshment process was developed by CTC Umwelttechnik of Switzerland. It uses a combination of mechanical and thermal treatment. In a first step the shredder light fraction is comminuted and Fe-, Cu- and Al-scrap are separated. In a second step the material undergoes a “thermal cleaning” at temperatures up to 2000°C. Thus, energy is recovered and inorganic components are “immobilized” and can be used for road constructions. (Schaub, 2002, Aldo et al., 2004a, Aldo et al., 2004b). Currently, there is not even a pilot plant in operation. The costs are estimated to range between 75 and 140 €/t.
• Thermoselect process
The process was developed by the Japanese company Thermoselect. The process is based on pyrolysis followed by a gasification process at temperatures up to 2000°C (Kiss, 1992, Yamada et al., 2004, Drost et al., 2004). The output fractions are synthesis gas, sulfur, water, metals and minerals. In Japan there are seven lines in operation while the only plant in Europe (Karsruhe, Germany) was shut down due to a series of problems. The cost are estimated to rage at approximately 140 €/t.

• “Schwarze Pumpe” process
The term “Schwarze Pumpe” is related to the name of its location which is a district of Spremberg (Germany). At this site the SVZ (Sekundaerrohstoff-Verwertungszentrum Schwarze Pumpe) operated a plant (Rabe et al., 1997, Anonymous, 2001, Hauptmann et al., 2004, Buttker et al., 2005). The input material (shredder light fraction mixed with municipal solid waste) was pelletized and fed to a gasification step. The main output was synthesis gas (approx. 75 %) which was used as feedstock for methanol, ammonia and formic acid production. Aside 8 % metals were obtained whereas about 17 % vitrified slag remained. In 2005 the plant was overtaken by Sustec Industries AG, but finally closed in 2007.

• Oxyreducer process
The oxyreducer or CITRON process was developed by the Swiss company Citron Holding AG (Brueggler, 2008). The process is feasible for a variety of waste. The material is pyrolyzed and the obtained gases are used to reduce some of the metal oxides. The output of the plant consists of some metal concentrates and about 50 % waste. The costs range between 100 and 200 €/t.

• PyroArc process
The PyroArc process was developed by the Swedish company ScanArc Plasma Technologies AB. The technology comprises a pyrolysis step followed by a vitrification of inorganic materials and a plasma decomposition of gases (Hetland et al., 2001). The products comprise fuel gas, leach resistant slag, metals and small amounts of dust. A pilot plant has been in operation since 1986. The costs range between 50 and 230 €/t.

In the case of mechanical separation, the main products are plastic granulates, sand and a so called fluff fraction which contains fibers, films and foams. Compared to thermal processes the effort is lower and the disposal costs are more economic. However, the technology still generates wastes that require incinerators or landfill sites. In the following the most important industrial post shredder technologies are briefly introduced.

• SRTL process
The SRTL (Shredder Residues Treatment Line) process has been developed by the Belgian company Galloo (Vandeputte, 1999, De Feraudy, 2000, De Feraudy, 2007). It uses mechanical separation (by shape factor), cleaning and at least two further steps of mechanical separation (by density). The resulting fractions are plastics (9 %), metals (30 %), waste derived fuel (13 %) and waste (48 %) (Anonymous, 2006b). The overall costs (including subsequent landfill) range at approximately 65 €/t (Reinhardt et al., 2004).
SiCon / TBS
The German companies SiCon and VW developed a mechanical process schedule to separate SLF into the main fractions of plastics (subdivided into PVC rich and poor), sand (fine mineral material) and fluff (Goldmann et al., 2007a, Goldmann et al., 2007b, Goldmann et al., 2007c, Goldmann et al., 2007d). The sand fraction can be landfilled while the fluff fraction is used as a filtration aid for sewage sludge dewatering and the plastics can be used as a reduction agent in the blast furnace process (Buergler et al., 2004, Buergler, 2008). The Austrian company TBS operates a PST plant using a similar technology and also producing plastics, fluff and sand.

SALYP process
The Belgian company Salyp developed a separation process which is based on a special method to separate plastics from waste (Stricker, 2001, Gisquiere, 2004a, Gisquiere, 2004b). Apart a fluff and a sand fraction, plastics are sorted into monofractions.

Other processes
It can be assumed that other companies, especially outside the EU, will operate plants to process SLF. The following processes / companies are mentioned in the literature (Reinhardt et al., 2004, Anonymous, 2006b, Jody et al., 2006):
- Cometsambre (COMETSAMBRE S.A., BE)
- R-Plus (ALBA R-plus GmbH, DE)
- Scholz (Scholz AG, DE)
- SULT process (Hachinohe, JP)
- WESA process (R-plus Recycling GmbH, DE)

NEW CONCEPT FOR TREATING SHREDDER LIGHT FRACTION

Fluff as potential source for fibers
Even if post shredder technologies are already far developed, in particular mechanical processes, it seems that there is still a considerable room for further improvements. Partially the post shredder technologies produce output streams which are feasible for a further recycling and, thus, commonly an economically marketing is possible. However, there are still a number of fractions that have to be landfilled or otherwise recovered. In order to increase the overall benefit of post shredder technologies it is necessary to change to properties of these fractions and to find attractive possibilities for a recycling.

Regarding mechanical post shredder technologies the so called fluff fraction has been determined as promising material to improve the environmental and economical performance. The fraction contains considerable portions of fibers which have already consumed a considerable amount of energy. Therefore, a re-use or recycling of fibers offers the opportunity to save costs and resources (Bartl et al., 2008a).

It has been reported that tire derived fibers can be used as additive in the bitumen industry (Bartl et al., 2005, Bahardoust et al., 2006). Test results on bitumen modified with tire derived fibers showed that the addition of fibers to bitumen, used for asphalt road pavements, increased the temperature range of application (Bartl et al., 2005). It is possible to replace well established fibrous products (Arbocel®) which are already in use for road pavements (Rettenmaier, 1991)
It has also been reported that TDF and fibers recovered from nonwovens can be used as viscosity modifiers (Bartl et al., 2006a, Bartl et al., 2006b). The investigations revealed a predominant effect of the fiber length (aspect ratio), independent of the origin of the fibers. It has recently been described that fluff obtained from shredder light fraction is a possible source for deriving fibers and their use as additive for construction materials (Bartl et al., 2008b).

**Deriving fibers from SLF fluff**

Fluff originating from shredder light fraction was dried and extricated from residual contraries such as small metals and minerals. In order to avoid entangling and to homogenize fiber length the material was further processed with a cutting mill.

For analysis purposes the material was sieved with mesh sizes between 100 and 1,500 µm. Three representative samples as shown in Table 2 could be identified. It will, however, be necessary to define a single mesh size to result in only two, a fiber rich and a fiber poor, fraction. The respective size will depend on the subsequent application.

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Size [µm]</th>
<th>Portion</th>
<th>Constitution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>&gt; 800</td>
<td>20 %</td>
<td>Fibers, residues of films; small particles adhering to</td>
</tr>
<tr>
<td>Intermediate</td>
<td>200 – 800</td>
<td>40 %</td>
<td>Contains both fibers and non-fibrous individuals</td>
</tr>
<tr>
<td>Fine</td>
<td>&lt; 200</td>
<td>40 %</td>
<td>Largely fiber free</td>
</tr>
</tbody>
</table>

Fiber length and width of the reclaimed fibers have been determined by an automated image analysis system (MorFi) which was originally developed for pulp characterization (Tourtollet, 2001, Passas, 2001). It was already demonstrated before that the system is also a useful tool for characterizing recycled fibers (Bartl, 2005).

In terms of fiber length there is a distinct difference between Arbocel® and SLF fluff, on the one hand and, tire and nonwovens derived fibers, on the other hand as demonstrated by the charts in Figure 1. The latter ones show a fiber length distribution with a maximum at about 0.5 mm. Both, Arbocel® and SLF fluff contain the highest portion in the smallest size class, most probably containing a significant portion below the detection limit of the MorFi (0.1 mm).

For the Arbocel® sample this effect can be explained by its native origin (ground cellulose). In the case of SLF fluff it seems very likely that a considerable portion is dust originating from ground foils and foams. For all reclaimed fibers the specific length can, of course, by influenced by the grinding conditions. In particular, all samples (SLF, tire, nonwovens) have been finally ground with a mesh size of 0.50 mm. It is, thus, not amazing, that the fiber length is within the same range (0.5 to 0.6 mm). Depending on the final application of the recycling product fiber length can be adjusted to the respective requirement.

It is clear that fiber width is not affected by the grinding process but a question of the fiber origin. The Arbocel® sample shows a quite broad distribution due to its native origin (ground cellulose). The SLF fluff sample is quite similar probably caused by a variety of man-made fibers exhibiting different diameters. In contrast, fibers derived from nonwovens and tires show a distribution which is significantly less broad. On the one hand, tire manufacturer use a quite small spectrum of fiber diameters. On the other hand, the results of the
nonwovens sample origin from a concept test using new material containing a single fiber material. However, it is demonstrated that fibers derived from shredder light fraction show, to a certain extent, a quite similar width than other reclaimed fibers as well as the commercial product Arbocel®.

CONCLUSION

Although stringent recycling quotas for end-of-life vehicles are in force in the EU still a considerable portion of shredder light fraction is still landfilled. Even if post (mechanical) shredder processes are already far developed an economic recycling is only possible for a limited fraction. In particular the situation for fluff needs to be further improved in terms of ecology as well as economy.

It is demonstrated in this study that fibers can be derived from shredder light fraction. Due to the complex composition of vehicles the recycled material still contains a considerable amount of (very fine) non-fibrous particles. However, in terms of fiber length and width the reclaimed fibers are comparable to well established products used in construction industry (e.g. Arbocel®) as well as to fibers reclaimed from other types of waste (e.g. fibers derived from end-of-life tires). Currently the performance of fluff derived fibers in asphalt pavement is under investigation. The possibility to substitute rather expensive additives offers the chance to change a costly waste stream into a marketable recycling product. Furthermore it can help to meet the quotas of the 53/2000/EC by 2015.

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