2 Brief Review of the Methods of Recycling of Polyurethane Foam Wastes

2.1 Recycling Methods

As mentioned in Chapter 1, polyurethanes (PU) are one of the most versatile groups of plastic materials, with a variety that stretches from flexible/rigid foams and thermoplastic elastomers to adhesives, paints, and varnishes. This variety is one of the reasons why development of cost-efficient recycling methods is very difficult. PU production is expensive compared with mass-produced plastic materials (e.g., polyolefin plastics), which is the reason for the development of recycling methods (i.e., physical, chemical and thermochemical and energy recovery) for PU wastes since the 1960s.

Recycling routes for PU can be divided into ‘mechanical (physical)’, ‘chemical’ and ‘energy’. Mechanical recycling covers grinding, compression moulding, adhesive pressing and bonding of PU wastes. Chemical methods (also called ‘feedstock recycling’) change the chemistry of the materials and refer to the breakdown of targeted bonds to recover valuable materials. Energy recovery refers to incineration of PU waste, decomposition (by pyrolysis or hydrogenation) and the combustion of products.

2.2 Mechanical Recycling

Mechanical (physical) recycling of PU wastes refers to one of the many forms of ‘particle recycling’: regrinding, rebinding, adhesive pressing, injection moulding and compression moulding. Grinding of PU wastes into powders and then reuse of these powders in different
ways constitutes a mechanical recycling approach. Usually, the wastes for this process come from factory trims and scraps from the production line, as well as post-consumer products. The resultant powder can be used as filler for generation of PU foams (PUF) or elastomers. In this case, the powders are usually added first to the polyol component in a PU production process. Moulded PU products can contain ≤20% regrind material without serious deterioration in physical properties, mechanical properties or performance. To be used as filler, the particle size of the PU powder should be <100 and 200 μm, and different milling and knife-cutting processes are needed.

In another process, shredded polyurethane foam (PUF) wastes can be rebound using pressure or heat. An adhesive binder is used to make vibration- and sound-dampening mats, floorings, sports mats, cushioning and carpet underlay. In a similar method known as ‘adhesive pressing’, PU granules in different shapes and sizes are coated with a curable binder and cured under pressure and heat, and are used predominately as automotive floor mats and tire covers. In another physical recycling method of PU wastes, reaction injection moulding (RIM) and reinforced-RIM parts can be ground into small particles, which can be moulded under high pressure and heat to form solid parts for the automotive industry. In addition, compression moulded solid parts such as pump and motor housings can contain ≤100% RIM regrind [1].

2.2.1 Rebinding

In rebounding, the final product is moulded PU from pieces of shredded flexible PUF, held together with a binder. Its relatively high density and excellent resilience make it appropriate for vibration- and sound-dampening, flooring, sport mats, cushioning, packaging and carpet underlays [1, 2]. Rebinding has been used for decades. Database surveys show that ≤50,000 tonnes of rebounding foams received from wastes are processed each year in Western Europe, and new applications are being developed. PUF scrap can be reprocessed by mixing scrap particles of particle size ≈1 cm with an appropriate
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diisocyanate [e.g., 4,4′-diphenylmethane diisocyanate (MDI)] followed by the form-shaping at 30–200 bar and 100–200 °C. In this process, PU-based construction boards with high resistance to water and moisture as well as insulation panels for use in new freezers or refrigerators can be obtained. In the same process, PUF can also be recycled to blocks that find use in carpets, sports mats or furniture. For example, the enormous amount of PUF recovered from scrapped vehicles may satisfy a great part (= 50% in the USA) of the market for carpet underlay. This recycling option is very important for scrapped PUF received from buildings and constructions but is more complicated (and frequently impossible) due to the use of flame-retardants in these materials. Rebinding of PUF can be carried out through batch moulding or continuous moulding, and the foam blocks are processed further to make parts and articles, resulting in trim which in turn can be reused in this process. One of the most important benefits in the mould–shape rebinding process is optimisation of material use and costs. In conclusion, the batch moulding rebinding process comprises collection → sorting → shredding → coating with binder → compressing shaping → activation of adhesive binder → curing of adhesive binder → fabrication of rebounded parts (Figure 2.1) [1, 3].

The quality of the final product of rebinding is dependent upon: types and grades of the foams used; particle size and uniformity of foam pieces; required density of the final product; quality of the binder as well as binder to foam ratio.
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![Diagram of recycling process]

**Figure 2.1** Typical rebinding equipment using batch moulding. Reproduced with permission from the European Diisocyanate & Polyol Producers Association, Brussels, Belgium. ©European Diisocyanate & Polyol Producers Association
2.2.2 Regrinding

Regrind technology (also termed ‘powdering’) involves reuse of ground PU waste as filler in the PUF or elastomer formulation and involves i) grinding PU material into a fine powder and ii) mixing powder with the polyol component to fabricate new PU. The first step necessary for PU recycling involves reduction of the particle size of the original PU product to a level that allows the material to be reprocessed in a secondary production step.

In this recycling method, the optimum particle size is 50–200 μm, depending on the application. Different types of PU waste products, which consist of old recycled parts or production waste (e.g., trimmings, scrap parts), are converted to flake, powder or pellets depending on the PU type that is being recycled. In most cases, this step can be accomplished by shredding or grinding the PU to provide the required media for recycling. This waste is typically a direct result of the trimming of slabstock buns and subsequent manufacturing into the finished product. For operations involving moulded foam, the waste is usually produced during the manufacturing process as a result of the flashing at the closing edges and venting holes of the mould which, in extreme cases, may amount to 6% of material waste depending on the size of the overall part. In the case of slabstock or flexible foam, ≤12% of cutoff waste should be expected, depending on the specific manufacturing process.

Several methods can be employed in the manufacture of small and fine particles. The first option is using a two-roll mill process: two rollers rotating in opposite directions and at various speeds create shear forces in the very narrow gap between them. The second grinding method (which has been used in pilot studies for flexible foam wastes) is based on the pellet mill process: two or more metal rollers press the PUF through a metal plate with small holes or a die. Other technologies (e.g., precision knife cutters) are under evaluation for grinding of flexible PUF. In addition, a process combining cutting and mixing involves a high-shear mixer installed in a polyol tank. The added benefit of this method is prevention of thermal degradation.
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of the powder during size reduction. Glass-filled RIM parts require special grinding processes. The impact disc mill appears to be an appropriate method for pulverisation of such very tough parts [4].

At the pilot-study scale, a high-shear mixer appears to be appropriate for providing the right quality of mixing. The step to operational activity, however, requires suitable metering of the powder alongside the polyol. The metering unit of the entire PU machine needs to be appropriate for the handling of filled polyols. Such technologies were developed when glass-filled RIM was first introduced into the market or when melamine powder was introduced into the industry for flexible PUF. The moisture content of the powder is important, and drying of the powder before mixing may be necessary.

One factor that limits the amount of scrapped PUF that can be recycled by regrinding is the viscosity of the polyol–fine particle mixture that can be handled by the processing equipment. In practice, this can be ≤15 wt% regrind if MDI and a polyol mixture is used, and ≤25% if toluene diisocyanate (TDI) is used as the isocyanate. The main problem of grinding processes for waste processing is that of economy: grinding of scrap PUF to <100–125 μm necessitates more energy consumption. PUF in automotive seating has been recycled using regrind processes. Data obtained from laboratory tests reveal that new moulded foam seats have been fabricated containing 15–20% recycled material and exhibiting excellent processing characteristics. Depending on foam type and filler loading, physical properties may be affected, so adjustment of material specifications may be required (Table 2.1).

The investment cost of first-generation equipment has limited the operational potential of this process to slabstock. Current developments are directed to providing economically viable processes to smaller operations. A typical scheme of regrinding technology is shown in Figure 2.2 [1, 4].
**Table 2.1 Comparison of the specifications of standard and recycled flexible car seat foams**

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Recycled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder content (%)</td>
<td>–</td>
<td>15</td>
</tr>
<tr>
<td>Indentation hardness (N)</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td>Compression set (50%)</td>
<td>5.6</td>
<td>7.0</td>
</tr>
<tr>
<td>Tensile strength (kPa)</td>
<td>152</td>
<td>144</td>
</tr>
<tr>
<td>Elongation at break</td>
<td>132</td>
<td>103</td>
</tr>
</tbody>
</table>


Bayer Corporation has invented a process for making energy-absorbent foam with PU wastes. Fillers that produce energy-absorbent foam have properties that are comparable to those prepared from ‘virgin’ materials.

**2.2.3 Adhesive Pressing**

Adhesive pressing is a rapid and simple recycling method. In this process, the surface of PU particles is coated using an adhesive binder and bonded in a heated press. It has been suggested that adhesive pressing is one of the oldest processes for physical recycling of flexible PUF. During the 1990s, its market potential was ≈10,000–20,000 tonnes per year in Western Europe and 50,000–60,000 tonnes per year in North America. In Europe, RIM particles are being recycled as underfloor heating pipes (which have a very great recycling capacity, especially in Germany) in buildings. A typical method is to mix PUF scrap particles with MDI followed by forming at 100–200 °C under 30–200 bar. This method has enabled useful materials for insulation panels, carpets and furniture to be created [1].
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Figure 2.2 Typical regrinding process for PU recycling. Reproduced with permission from the European Diisocyanate & Polyol Producers Association, Brussels, Belgium. ©European Diisocyanate & Polyol Producers Association

2.2.4 Compression Moulding and Injection Moulding

The compression process involves moulding PU particles at 180 °C and under 350 bar to flow the ‘neat’ particles together (without