WHITEPAPER

Continuous Chemical Recycling of Polyurethane

Polyurethane (PU) recycling technology enables the continuous depolymerization of end-of-life polyurethanes, converting complex PU waste streams into recycled polyols. These can be reintegrated into industrial applications and contribute to closing material loops in line with circular economy principles.

Introduction

The PU recycling technology was developed within an industrial collaborative project involving KraussMaffei Extrusion, KraussMaffei Technologies, BASF, Rampf, and Remondis. As part of an ongoing feasibility and commercialization program, the technical and economic potential of this continuous glycolysis process is currently being evaluated.

Continuous chemical recycling of polyurethane represents a promising route to closing material loops, particularly for complex end-of-life waste streams that may contain up to 30% non-PU contaminants.

This whitepaper presents a continuous glycolysis process implemented in a co-rotating twin-screw extruder and demonstrated using rigid PU foam from end-of-life refrigeration appliances. The process converts these waste streams into recycled polyol (rPolyol), which can be reused in polyurethane systems. In doing so, it addresses both circular economy objectives and the requirements of industrial-scale processing.

Relevance of Polyurethane Recycling

Polyurethane is a versatile material with unique property profiles, making it indispensable across a wide range of applications. These include insulation for refrigeration appliances, cushioning for automotive seating and mattresses, as well as numerous industrial uses. These properties arise from the crosslinked polymer structure of PU, which significantly complicates recycling compared to thermoplastics.

Figure 1: Recycling loop for polyurethane from refrigeration appliances

At the same time, increasing regulatory pressure, evolving sustainability strategies, and broader societal expectations are driving demand for circular material use. For polyurethane, this results in several key challenges:

- Establishing largely closed-loop recycling systems.
- Demonstrating sustainable and economically viable processing routes.
- Preserving material properties required for established applications.

Current Status of PU-Recycling

At present, the majority of polyurethane waste is recovered through energy recovery, for example via co-incineration in the cement industry. Mechanical recycling routes do exist, such as use as oil absorbents or fillers; however, these approaches are limited in terms of value retention, material quality, and application scope.

Within the European Union, a structured take-back and recycling infrastructure is currently established primarily for PU derived from end-of-life refrigeration appliances.

Challenges of Polyurethane Recycling

Future recycling solutions for polyurethane must address several inherent challenges. End-of-life PU waste streams often contain significant levels of contaminants, which must be reduced or removed to prevent adverse effects on downstream processing and recyclate quality.

In parallel, waste volumes are substantial and expected to increase further. This necessitates continuous processes capable of handling large material flows efficiently, reliably, and at industrial scale.

Figure 2: Recycled polyol containing impurities

Process Methodology

In the chemical recycling of rigid PU foam from end-of-life refrigeration appliances, the material is fed in powdered form via a gravimetric dosing system into the feed section of a co-rotating twin-screw extruder (ZE BluePower). The PU powder may contain up to 30% organic and inorganic contaminants.

Immediately downstream of solids feeding, the liquid depolymerization agent is introduced into the extruder via a separate gravimetric dosing system using appropriate injection units. As the process is continuous and reactive, precise and stable dosing of all components at a defined ratio is critical for ensuring process stability and consistent product quality.

Following the feed section, both streams are homogenized using dedicated kneading and mixing elements and conveyed into the reaction zone. There, the combined input of shear energy and external heating raises the material temperature to reaction conditions in the range of 200 °C to 300 °C.

At these temperatures, the three-dimensional crosslinked PU structure is progressively cleaved by the depolymerization agent. The result is a recycled polyol (rPolyol) containing residual contaminants.

Figure 3: Co-rotating twin-screw extruder as the reaction zone for depolymerization

Reaction Control and Residence Time

A key parameter governing depolymerization performance is the mean residence time within the extruder. Longer residence times promote a higher degree of solvolysis.

Compared to batch processes, residence times in twin-screw extrusion are typically in the range of 30 to 120 seconds—approximately one order of magnitude shorter than in conventional batch reactors. Residence time can be tailored through extruder length (up to 64 L/D), screw configuration, and operating conditions, such as reduced screw speeds in the range of 100 to 200 rpm.

Potential side reactions can be mitigated through appropriate process control. The narrow residence time distribution characteristic of co-rotating twin-screw extruders is advantageous, as it limits excessive thermal exposure of individual material fractions and thereby reduces the formation of undesired by-products.

Contaminants present in the liquid rPolyol are removed using suitable filtration systems, selected according to particle type and size. Prior to filtration, the product is cooled to a defined filtration temperature. After filtration, it is further cooled and transferred to intermediate bulk containers or storage tanks for subsequent processing.

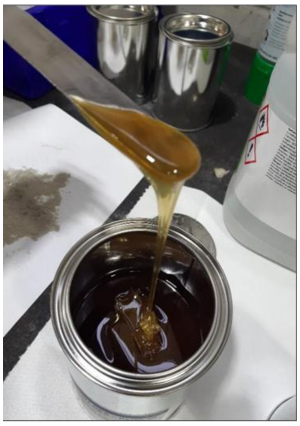

Figure 4: Purified recycled polyol

The resulting recycled polyol can then be incorporated into polyurethane systems at defined ratios, enabling, for example, the production of insulation materials for refrigeration appliances with adjustable recyclate content.

Transferability to Other PU Waste Streams

The underlying process concept is, in principle, transferable to polyurethane waste streams from a range of applications. In the present development project, the focus was deliberately placed on rigid PU foam from end-of-life refrigeration appliances due to the availability of well-defined waste streams and established collection infrastructures.

In practical implementation, however, process parameters and additives must be adapted to the specific characteristics of the input material and validated through experimental and analytical methods.

Removal and Utilization of Contaminants

A key advantage of the continuous extrusion process is its high tolerance to contaminants. Due to current recycling practices for refrigeration appliances, the PU input stream may contain significant levels of impurities. These include thermoplastics such as polystyrene and PVC from housings and seals, as well as ferrous and non-ferrous metals from attached components.

Regulatory requirements result in these contaminants being reduced to very fine particle sizes during preprocessing. As a consequence, complete separation from the PU powder prior to extrusion is technically challenging. Depending on process conditions, contaminants may account for up to 30% of the total material stream.

In contrast to batch processes—which can be sensitive to elevated thermoplastic content and prone to operational issues such as fouling or blockage—the co-rotating twin-screw extruder exhibits high robustness toward such impurities. The system is self-wiping, and all downstream equipment is designed for continuous operation. Contaminants can therefore be effectively removed in downstream filtration units. Where technically feasible and application-relevant, the resulting filtration residues can be directed to further use in suitable applications.

Figure 5: Twin-screw extruder ZE BluePower for the depolymerization of polyurethane into recycled polyol

Project Partners and Contributions

The development of the PU recycling technology was enabled by an interdisciplinary consortium:

- KraussMaffei Extrusion GmbH: extrusion technology, process development, and operational expertise from the Technology Center Laatzen.
- KraussMaffei Technologies (RPM Division): expertise in reaction process machinery and processing of polyurethane systems containing recyclates.
- BASF: supply of PU raw material systems, as well as support in process development, analytics, and utilization concepts for filtration residues.
- Rampf Advanced Polymers: expertise in discontinuous PU recycling, formulation of depolymerization agents, and analytical methods.
- Remondis: supply of PU from end-of-life refrigeration appliances, as well as expertise in recycling processes and regulatory frameworks.

Advantages of Depolymerization of PU Waste

Compared to discontinuous batch processes, continuous extrusion-based depolymerization enables industrial-scale processing of large PU waste streams with elevated contaminant levels.

Depending on application requirements, significant recyclate contents (approximately 25%) can be incorporated into new polyurethane systems. The remaining fraction consists of virgin material required to meet specified performance and material properties.

Given the long service life of rigid PU foam applications—such as in refrigeration appliances—there is also potential for multiple recycling cycles and repeated reintegration into suitable systems.

Sustainable and Economically Viable PU Recycling

The PU recycling technology supports the industrialization of continuous chemical recycling of polyurethane. It enables scalable, contaminant-tolerant, and economically viable processing of end-of-life PU, representing a key building block for a future circular economy in the polyurethane sector. Capital investment depends on factors such as the properties of the input material and the selected machine configuration. Additional considerations include the scope of upstream and downstream processing equipment, as well as the targeted throughput capacity.

Based on current assessments, polyurethane systems containing recyclate are cost-competitive with systems based on virgin materials. Industrial implementation is currently in the early market adoption phase. The use of recyclates enables carbon circularity, reduces product carbon footprint, and contributes to the substitution of fossil-based raw materials, resulting in substantial sustainability benefits at industrial scale.