

Meeting Premium Automotive Lighting Requirements with Circular Polymers: Recycling Challenges and Material Solutions in the NALYSES Project

K. Pupovac¹, M. Roppel¹, J. Helmig¹

1: Covestro Deutschland AG, Kaiser-Wilhelm-Allee 60, 51373 Leverkusen

1. Abstract

The NALYSES project investigates the specific challenges of recycling plastics from automotive headlights. This research paper analyses the fundamental difficulties in the sorting of shredded headlight systems, the effects of material degradation on optical properties and the challenges of removing coatings. The results show that for high-quality optical components in automotive lighting, chemical recycling and its derived products are the most promising approaches to achieve the required quality standards in terms of transmission and optical purity. While adequately processed mechanical recyclates (e.g. Makrolon® R) are certainly suitable for demanding automotive applications, the specific optical requirements in lighting technology pose a special technical challenge that requires specialized consideration (e.g. Makrolon® RE or Makrolon® RP).

Keywords: NALYSES project, automotive headlight recycling, automated sorting, post-consumer recyclates, optical properties, decoating technologies, recycling methods, REACH regulation, polycarbonate, automotive headlamp

2. Introduction

The automotive industry is faced with the challenge of increasing recycling rates in accordance with expectations of the upcoming End-of-Life Vehicles Regulation (ELVR) while meeting the highest quality standards. Automotive headlamp systems are subject to extremely demanding requirements in terms of optical and mechanical properties. The NALYSES project, a research cooperation between Forvia/HELLA, BMW, Covestro and additional partners, is dedicated to the systematic evaluation of the potentials and limitations of various recycling approaches.



The integration of recycled materials into innovative headlamp systems requires compliance with stringent quality criteria, whereby the optical properties and long-term stability are of essential importance.

3. Limitations of Automatic Sorting in the Extraction of High-Quality Polycarbonate Fractions from Headlamp Systems

The investigations carried out reveal significant limitations of current automated sorting technologies. Defined shredded headlamps were sorted in a two-stage process using various state-of-the-art systems. Two polycarbonate-containing fractions were extracted from the starting material, together accounting for approximately 19% of the total volume, which is significantly lower than the polycarbonate content known from the bill of materials (BOM). According to the machinery parameters, the purities achieved amount to approx. 96% for the primary fraction and approx. 70% for the secondary fraction (Fig. 1).

Despite the high purity of the primary fraction, visual analysis indicates a significant amount of black material in addition to the desired transparent components. The secondary fraction also has an increased proportion of heterogeneous polymer materials. Although further purification to obtain a fraction with an increased degree of purity and transparency would theoretically be achievable through additional sorting cycles, this would lead to considerable material losses. Furthermore, detailed economic investigations regarding the cost-effectiveness of such additional processing steps are required.

The results illustrate the fundamental problem of automated sorting of shredded headlamp systems. The near-infrared spectroscopy implemented in modern sorting systems reaches its technical limits here, as coatings, contamination and surface defects significantly impair spectroscopic detection. The complexity of modern headlamp systems with their various material composites makes effective automated sorting even more difficult.

This sorting problem currently prevents the fully automated extraction of a sufficiently pure transparent polycarbonate fraction from shredded headlamp systems that would meet the stringent quality requirements for optical applications in automotive lighting. The remaining contamination and the increased proportion of black components in the separated fraction prevent the direct recycling of the material for high-quality optical components.

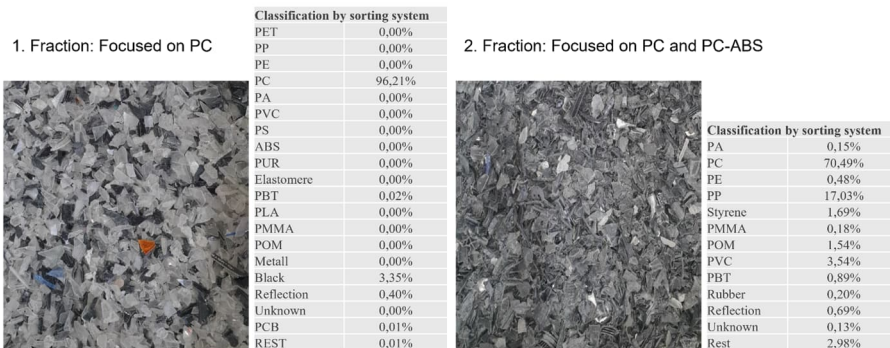


Figure 1: Polycarbonate fractions from automated sorting trials

4. Evaluation of Post-Consumer Recycled Polycarbonate from Automotive Headlamp Cover: Optical Performance Analysis

The headlight cover is an essential component of the automotive headlamp system. It ensures optimal light distribution and at the same time protects the sensitive internal components from environmental influences such as dust, moisture and stone chips. Due to its excellent optical clarity, polycarbonate enables excellent light transmission of modern headlight covers. This feature allows for optimal visibility during night rides or adverse weather conditions. The special surface coating makes the lens scratch-resistant and complies with ECE and SAE regulations. Due to its size and purity and easy access for dismantling, the headlight cover is a particularly attractive component for recycling and was therefore investigated in more detail.

The research focused on the analysis of post-consumer recyclates (PCR), which reflect the potential changes in the quality of the material due to environmental influences during the life cycle. Polycarbonate (PC) PCR from headlight covers of vehicles from three different model year groups was evaluated:

- Group I (built 1990-2001)
- Group II (built 2002-2006)
- Group III (built 2007-2018)

To investigate the optical properties of the PC PCR sample, the shredded PC PCR (Fig. 2) was processed into a sample plate using a microcompounder (Xplore MC 15 HAT) (Fig. 3).



Figure 2: PC PCR from shredded headlight covers (from left to right: Group I, Group II and Group III).

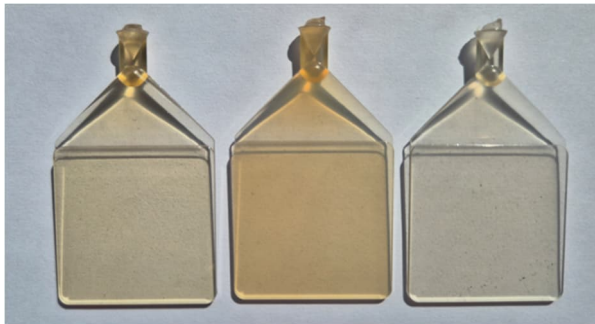


Figure 3: Sample plates made from the PC PCR from shredded headlight covers (from left to right: Group I, Group II and Group III).

Table 1 shows the optical properties of the three PC PCR materials examined in comparison to primary fossil material (unpainted) that are essential for the headlight covers.

The reference value of primary fossil polycarbonate reaches a transmission value of 89%. All recycled materials tested have lower transmittance values, with group II showing the lowest value at 72%, followed by group I at 79%. Group III, the PC PCR sample from the youngest group of construction years, achieves the best value among recycled materials at 81%.

Other optical features, Yellowness Index (YI) and haze, follow the same trend and show significant quality losses. While the primary fossil material has a YI of 1 and a haze value of 1%, these values rise to 25 and 42% respectively for PC PCR materials.

In addition to PC PCR material, unpainted PC post-industrial recyclate (PIR) was also analysed. This PC PIR material originates from polycarbonate production waste from headlight covers. As expected, this sample shows optical properties that are almost identical to those of new material (Table 1).

Sample	Transmission (%)	YI	Haze (%)
Primary fossil PC	89	1	1
PC PIR	87	2	1,5
PC PCR Group I	79	17	18
PC PCR Group II	72	25	42
PC PCR Group III	81	8	35

Table 1: Optical properties of primary fossil PC and PC PCR materials from shredded headlight covers (measured at 1.5 mm sample thickness).

It should be considered that all PC PCR materials examined contain a coating layer. In headlight covers from group I and II, especially in vehicles that have been used for a longer period, this coating partially detaches (delamination/exfoliation of the coating layer), resulting in non-uniform optical characteristics.

The test results show a significant reduction in the optical properties of the PC PCR materials compared to the reference material as well as to the PC PIR sample. The optical performance of the PC PCR material is significantly impaired by various aging processes, including UV radiation, temperature changes, moisture exposure as well as oxidative and chemical degradation processes of the polymer. The paint coating is also subject to environmental damage processes, which contribute to the further deterioration of the optical properties of the PC PCR material. The reduced optical quality of the evaluated PC PCR materials can affect light output and visibility and consequently compromise driving safety. The UN/ECE regulations define precise requirements regarding light distribution and intensity for headlight covers in vehicles, which must be met within specified tolerance ranges. Consequently, the use of such aged PC PCR materials for headlight covers could lead to non-compliance with these normative requirements.

5. Hazardous Substances: Regulatory Compliance Challenges for Automotive Circular Economy

In addition to the technical requirements, the targets for recyclates in vehicles are also linked to various other regulatory provisions of other EU legislation.

Recyclates may contain legacy substances, substances of very high concern (SVHC) or persistent organic pollutants (POPs), due contamination over lifetime or due new regulatory situation since the product was placed in the market. The REACH Regulation (EU, 2006) defines these pollutants and their threshold values. Products, including recyclates, placed on the market must adhere to this regulation.

The analytical examination of the PC PCR materials from shredded headlight covers has detected critical chemicals, mainly in the older group I and II. These are mainly additives such as UV absorbers, which either exceed limit values (detected in PC-PCR material of

groups I and II) or are included on the Candidate List of Substances of Very High Concern (SVHC list) (detected in Group III).

The presence of these substances in the waste stream to be recycled can be an obstacle to the circular economy as regulation evolves and products fulfil the requirements at the moment they are placed in the market. Chemical recycling can play a key role as it may support the management of plastic waste with otherwise hard to manage legacies (see section 7).

6. Challenges and Technologies for Removing UV-Coatings from Polycarbonate Headlight Covers

Polycarbonate headlight covers use UV-cured clearcoat technology, proven effective for over 30 years across major automotive markets. This coating, however, poses a significant challenge for the recycling of high-quality polymer materials at the end-of-life (EoL) term and consequently occupies a central position in the circular economy consideration.

For the efficient recycling of automotive headlamps, the complete separation of the UV-cured coating layer is of essential importance. Residual paint components act as contaminants within the recyclate matrix. Furthermore, these residual elements, in conjunction with polymer ageing significantly compromise the optical properties of the recycled polycarbonate substrate (see Section 4). Additionally, also the mechanical properties of the material are significantly impaired as well (see Fig. 4). To quantify the mass ratio between the polycarbonate substrate and the applied coating layer in headlight covers, a dimensional analysis can be used. For conventional polycarbonate headlight covers with a thickness of 2.5-3.2 mm (density: 1.2 g/cm³), a very thin UV-curable clear coat of only 10-15 µm (density: 1.1 g/cm³) is applied. This results in an extremely low mass share of the paint in the total structure of 0.26-0.53%.

Despite the minimal mass content of the coating, the properties of the recycled polycarbonate can be significantly compromised due to the cross-linked polymer structure and differentiated chemical properties of the coating.

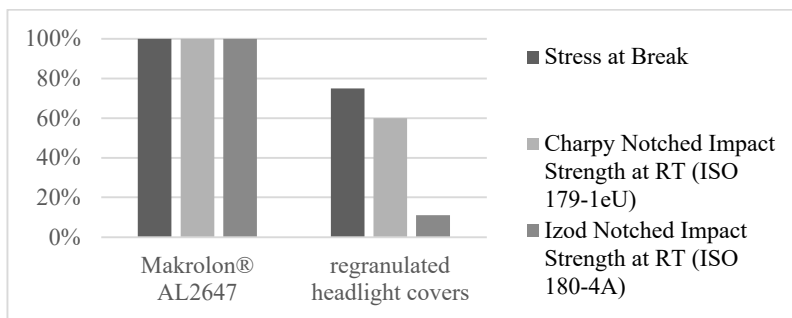


Figure 4: Percentual comparison of mechanical properties for primary fossil PC and regranulated headlight covers – impact of coating residuals visible

To solve this problem, various mechanical and chemical processes were investigated to enable the separation of the coating layer from the polycarbonate. The available mechanical recycling technologies for the separation of coating and polymer substrate can be classified into four distinct categories (Fig. 5):

Primarily, there are purely mechanical separation processes, which differentiate the material properties between rigid, brittle coating and ductile polycarbonate, with the interphase region having the lowest cohesion strength. In these processes, precise energy dosing is essential to achieve efficient separation with simultaneous substrate preservation.

Solvent-based processes focus on the selective solubilization of the coating matrix while preserving the polymer substrate ("Keep the polymer" strategy). The selection of non-aggressive media to avoid polycarbonate degradation is of critical importance.

In contrast, in physical recycling, the polymer substrate is specifically solubilized, while the coating persists as a solid particle and can be separated by filtration processes ("Dissolve the polymer" strategy).

The fourth category of methods includes melt filtration techniques, in which variable filter systems and mesh sizes are used to separate heterogeneous materials or eliminate contaminants.

Within the framework of the present study, extensive experimental series were carried out with PC PIR materials. These evaluations were carried out both in Covestro's internal laboratories and at various external technology providers to analyse a wide range of decoating processes.



Figure 5: Recycling technologies for the separation of coating

The sample selection was carried out systematically to ensure comparable evaluation conditions for the various technological approaches, which enabled a comprehensive assessment of the effectiveness of the decoating methods.

The evaluation of various decoating methods for UV-polymerized hard coatings on polycarbonate demonstrates a heterogeneous spectrum of effectiveness (Fig. 6). In the field of mechanical processes, the Impact Force methodology proved to be efficient, while evaluation results are still pending for dry abrasive, shock wave and blasting processes. Laser-based approaches and cryogenic crushing processes proved to be unfeasible.

Particularly promising results were achieved in the field of dissolution processes, where all three cooperation partners were able to achieve successful coating separation through physical recycling using substrate solubilization.

Melt filtration with variable mesh sizes also led to positive results for two partners. In the solvent-based processes with substrate preservation, two out of four partners were able to document successful results.

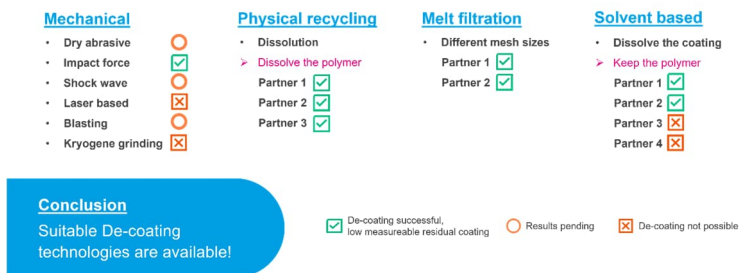


Figure 6: Evaluation of decoating methods for UV hard coatings

In summary, it can be stated that adequate decoating technologies exist, with dissolution and solvent-based processes in particular showing significant potential. A reduction in the contaminant concentration from an average of 0.39 percent by weight to ≤ 0.03 percent by weight was achieved. It should be noted, however, that despite significant visual and quantitative coating removal in the final material, minimal paint particles were still

detectable. This is probably due to the limited laboratory scale of the investigations so far, whereby the evaluated methods are not yet optimized for industrial applications in Europe. Furthermore, it must be concluded that the currently available processes do not reach the necessary purity parameters to meet the stringent requirements for transparent, high-optical applications.

7. Innovative Recycling Approaches to Achieve Optical Quality Standards

The NALYSES project examined recycling challenges where conventional methods had not achieved sufficient levels of purity for optically challenging materials. In this context, the project analyzed chemical recycling approaches that were developed outside the NALYSES framework. Research has shown that depolymerization into monomers or other basic chemical building blocks enables maximum separation of all contaminants and thus offers significant advantages over conventional mechanical recycling processes.

Investigations conducted outside the project demonstrated that during the depolymerization process, coating components are completely separated, whereby cross-linked structures remain as insoluble residues and can be eliminated by filtration processes. At the same time, metallic coatings and other additives, especially critical ones, are efficiently separated.

The sequential repolymerization technique enables a precise adjustment of the molecular weight distribution and consequently the reconstitution of the original material properties. This process yields material that achieves transmission values and yellowness indices that are common for primary material made of fossil-based materials, which meets the qualitative requirements. At the same time, modern, REACH-compliant additive systems can be implemented in a targeted manner.

8. Conclusions

The investigations carried out in the NALYSES project demonstrate significant limitations of conventional recycling methods for polycarbonate from automotive headlamps. Automated sorting of shredded systems does not achieve the required purity levels for high-quality optical applications. Manual pre-sorting processes are more effective, but from an economic point of view they are often not practical for industrial implementations.

The identified complex degradation mechanisms manifest themselves in reduced transmission values as well as increased yellowness indices and inhibit direct material reuse in optical components. The coating systems of modern headlight covers resist mechanical and chemical decoating processes without affecting the base material.

Within the NALYSES project, several existing Covestro materials were examined. These include mechanically recycled polycarbonate grades Makrolon® R, which Covestro had

previously developed specifically for selected automotive applications. This commitment to mechanical recycled circular solutions is further demonstrated by Covestro's End-of-Life vehicle initiative in China, supported by the German Agency for International Cooperation (GIZ). In this initiative, Covestro in collaboration with partners had developed innovative materials, Makrolon® RV and Bayblend® RV, from end-of-life headlight covers, demonstrating practical applications of the close loop concept for automotive components while advancing potential standards for vehicle material circularity.

The NALYSES project also examined renewable attributed materials (Makrolon® RE) and chemical recycled attributed materials (Makrolon® RP), which present themselves as the most technically feasible method for addressing identified problems simultaneously. The analysis confirmed that complete depolymerization reliably eliminates coatings, degradation products and legacy chemicals. The subsequent repolymerization enables the production of a material with optical and mechanical properties identical to primary material in compliance with current regulatory requirements. The results from the NALYSES project underline the need for further development and industrial scaling of chemical recycling processes as an essential prerequisite for the realization of circular economic concepts for engineering polymers in demanding optical applications.

9. Acknowledgments

For parts of this paper, the following applies: This research and development project is funded by the German Federal Ministry of Research, Technology and Space (BMFTR) within the “NALYSES – Sustainability-optimized life cycle assessment of technologically highly complex products using the example of automotive lighting” (funding number 02J21E105) and managed by the Project Management Agency Karlsruhe (PTKA). The authors are responsible for the content of this publication.