MARELITT Baltic

Interreg Baltic Sea Region

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Executive Summary

Recycling options for Derelict Fishing Gear

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August 2018, Stralsund

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The project is co-financed by the Interreg Baltic Sea Region Programme 2014-2020. The information and views set out in this report are those of the author only and do not reflect the official opinion of the INTERREG BSR Programme, nor do they commit the Programme in any way.

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Acknowledgements: Recycling trials with derelict fishing gear were carried out at Vecoplan AG, Bad Marienberg (Germany), Hochschule Magdeburg-Stendal (Germany), CleanCarbonConversion/EXOY Freienbach (Switzerland), and the Unit of Technology of Fuels (TEER) of the RWTH Aachen (Germany). Physical and chemical analysis was conducted at Magdeburger Kunststoff-Service Center (MAKSC), Magdeburg (Germany), Erema, Ansfelden (Austria), Plastix Global, Lemvig (Denmark), and Tönsmeier Entsorgungswirtschaft, Porta Westfalica (Germany). We are grateful for all trials and contributions that were carried out far beyond contracts and economic value by all companies and institutions involved. Many thanks to all the people who worked towards finding solutions for the technical challenge of DFG recycling for their highly motivated engagement.

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1. Introduction

As part of the MARELITT Baltic project, WWF Germany has carried out recycling trials with derelict fishing gear (DFG) retrieved from the German Baltic Sea. MARELITT Baltic is an EU-funded INTERREG Baltic Sea region project with the aim to mitigate the impact of DFG on the Baltic Sea marine environment. WWF Germany leads work package 4 (WP4) which results in recommendations for the handling and processing of retrieved DFG in the form of a DFG treatment scheme. The scheme can then be adapted to other countries and marine ecoregions where lost fishing gear is retrieved and collected in fishing harbours.

MARELITT Baltic WP4 covers:

- a survey of harbour infrastructure (led by Keep the Estonian Sea Tidy (KEST), M. Press 2018)
- handling and pre-processing of retrieved DFG in ports (KEST, in prep.)
- a survey of logistic requirements and economic viability of DFG recycling (WWF Germany)
- recycling trials to evaluate the technical feasibility (WWF Germany, this report).

All of these aspects feed into the DFG treatment scheme. As such, the treatment scheme provides recommendations for future DFG retrieval operations to develop a pathway for DFG recycling that can be applied also in the framework of the EU plastics strategy.

This report on technical feasibility describes in detail the results of all DFG recycling trials and the physical and chemical properties derived to evaluate the material quality of lost fishing gears retrieved from the Baltic Sea. The aim of this report is to provide a baseline of technical feasibility and processing options for retrieved fishing gear. The analyses and trials carried out lead to recommendations of how retrieved fishing gear can be treated to enter the value and recycling chai

Fig. 1.1: Derelict fishing gear retrieved from the Baltic Sea. Lost fishing nets are frequently entangled with a large number of other waste items. Left: Gillnets with styrofoam floats and poles. Middle: Trawl nets containing a fire hose. Right: Shell of an oxygen tank and end piece of a fire hose mixed with nets and other marine litter.

2. Recycling

With the aim to evaluate the potential of lost fishing gear for the plastics value chain, the focus was placed on the two predominant waste management pathways: material recycling and thermal processing. A wide range of experiments from pre-processing, shredding and fibre washing to high-temperature thermal polymer evaporation was carried out. Most contacts to companies dealing with the preparation of materials for recycling, the chemical analysis, and the thermal processing were provided by MARELITT Baltic Associated Partner Tönsmeier Entsorgungs GmbH, one of the largest recycling and waste management companies in Germany. Pre-processing of all materials was conducted with participation of WWF Germany in the technology centre of Vecoplan AG in Bad Marienberg, Germany. Vecoplan AG builds industrial shredders for waste processing, and the technology testing included industrial washing and density separation stages. Material recycling trials were carried out at the Technical University of Magdeburg-Stendal by Prof. Dr. Gilian Gerke and her team, who has one of the rare research groups with experience in the field of DFG processing. The material recycling trials were conducted by Dr. Gunter Weißbach as the chief laboratory scientist, who had worked with ropes and nets from sea-based samples before. Thermal processing included a laboratory-scale pyrolysis experiment carried out by Thomas Horst and Johann Hee at the Technical University of Aachen in the Unit of Technologies of Fuels (TEER) led by Prof. Dr. Peter Quicker. A high-temperature evaporation process termed "steam reforming" was conducted at EXOY's test reactor in Freienbach, Switzerland. The major results of the physical, mechanical and chemical analysis and all processing steps are summarised below.

2.1 Preparation for recycling

When retrieved from the sea, DFG is a highly mixed material that contains metal anchors, chains, organic matter such as mussels and dead fish and other marine litter as well as nets, ropes, float and sink lines. Between two and four handling stages are necessary to prepare retrieved fishing gear for either thermal or material recycling. All processing trials were conducted at Vecoplan AG's technology testing centre in Bad Marienberg, Germany.

1) First, pre-processing is required to remove large metal fragments, rocks and other disturbing substances that cause severe wear on shredding blades or other cutting devices. The separation of DFG into ropes, trawl netting and gillnets is required prior to shredding when aiming for material recycling.

2) In the second processing stage, the material is shredded. After this step a separation of fibres into individual fractions is technically challenging.

3) Density separation: DFG retrieved from the sea is typically heavily entangled, such that float and sink lines cannot be manually removed.

The lead weights in gillnet sink lines cause toxic contamination and can render an entire fibre batch unusable. Density separation in saline solution facilitates the removal of heavier lead fragments and sediments from the lighter polymer fibres. The floating fibre fraction can be extracted from the surface of the solution. In practical trials, the fluffiness of the fibres caused fine-grained sediments and small lead fragments to be trapped. Density separation alone did therefore not result in a clean separation of fibres from disturbing substances. In a second density separation stage, the extraction of high-density polyamide (PA6) from low-density polyolefins (polypropylene PP, polyethylene PE) was tested. In fresh water, the PA6 fibres should sink while PP/PE fibres are expected to float. Each fraction can in principle be extracted either from the surface or from the separation tank floor. As in the first density separation stage, the fluffiness of the PA fibres prohibited a clean separation, and residual contamination was present in all fractions. On the other hand, density separation substantially reduced the lead contamination by approximately a factor of ten. Sediments that would otherwise have further reduced the quality of the washing process were also removed. Density separation is thus highly recommended when fibres are prepared for material recycling.

4) Fibre washing: Different types of industrial washing systems are available on the market. At Vecoplan's technology centre, a Hydrodyn friction washer was available. Fibres are diluted with a washing liquid resulting in a 3% solid material concentration liquid. This liquid is pressed through two counter-rotating discs with grooves. The rotation causes a centrifugal force that guides fibres to migrate outwards along the grooves. The friction between the discs effectively expells sediments and other organic particles with the washing liquid. Washing improved the fibre quality visibly. However, the fluffiness of the material still caused small organic (wood) and lead fragments to remain mixed into most of the input materials. The best washing results were achieved with pre-sorted net and rope fractions of almost uniform quality and polymer type.

Recommendations

Pre-processing, i.e. the removal of large metal pieces such as anchors, chains, cables and larger rocks, is essential for all further processing steps. Pre-processing can best be implemented directly in the landing harbour to avoid unnecessary weight during transport. Shredding with industrial shredders is unproblematic in case the shredder contains a safety-stop with back rotation. Without a safety-stop mechanism and in small-scale cutting mills fibres cause system blocking and extensive motor heating and machine wear. Density separation should be considered a necessary step to minimise contamination with residual sediments and toxic lead fragments. Industrial friction washing works well for monofilament fibres, but is less efficient for woven fibres (trawl netting). Separation of individual rope and net types is beneficial for all processing stages and is required to obtain comparably uniform samples for material recycling.

Fig. 2.1: Manual pre-sorting of DFG lifted with a crane to facilitate access. Metal items, canisters, rocks and other large disturbances were manually removed to avoid machine damage during shredding.

Fig. 2.2: Ropes (left), trawl nets (middle panels) and gillnets (right) after removal or all disturbances. © Falk Schneider

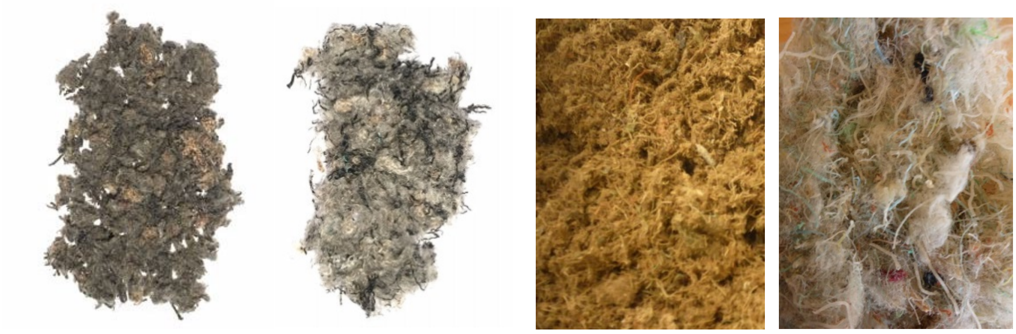

Fig. 2.3: Shredded trawl nets (left panels) and gillnets (right panels) before and after friction cleaning. ©Falk Schneider (left panels), Andrea Stolte (right panels).

2.2 Chemical analysis

A detailed chemical analysis was conducted by MAKSC GmbH on five different samples of retrieved DFG. The chemical analysis confirmed the four expected dominant polymer types in fishing gear: PA6 and PET as high-density polymers, and PP, PE as polyolefins. None of the five analysed samples resulted in a pure single-type polymer fraction. All samples, including the PA6-dominated gillnet samples and the PET-dominated ropes, showed contamination with polyolefins. The analysis of hazardous substances followed the EU REACH protocol and revealed high lead concentrations of up to 360 ppm, a factor of four higher than the limit in the EU packaging directive. Initial fibre concentrations were as high as 3 grams per kg of shredded gillnet material. Fibre processing and density separation have reduced the initial lead concentration in the gillnet-dominated sample by a factor of ten.

While the high lead concentrations are known to originate from sink lines, the origina of an enhanced chlorine concentration in two samples could not be traced.

Hence granulation and recycling of DFG into consumer goods is restricted to DFG fractions without potential toxic contamination.

Recommendations
Lead lines should be removed as far as possible to reduce toxicity in the final fibre batches. The better the level of pre-sorting, the higher the resulting material quality in terms of uniform polymer content and reduced contamination with substances listed under REACH. A REACH analysis prior to granulation for material recycling is highly recommended.

Fig. 2.4: Lead-line extracted from gillnet-dominated samples. © Gerke & Weißbach 2018

2.3 Physical and mechanical analysis

A detailed analysis of the physical and mechanical properties was commissioned to allow for comparison of DFG recyclates with other recyclates on the market. Tensile strengths and melting properties (melt flow indices) are found to be comparable to recyclates generated from end-of-life fishing nets. Elongation at breaking strength and impact strength are significantly reduced in DFG test specimen, which is likely a direct consequence of residual impurities that could not be completely removed from fibres retrieved from the seafloor. A lower breaking and impact strength of the DFG test specimen are expected to result in less durable products, which might limit injection moulding and other applications.

Recommendations
Pre-sorting of rope and net samples is essential to ensure material quality. Several washing stages will facilitate the removal of impurities resulting in more uniform material properties and should be considered in larger-scale processing operations in the future.

3. Recycling trials

Thermal processing and material recycling were tested with gillnet-dominated input material. This type of material was considered the most challenging because of the contamination with lead from sink lines, sediments, and organic matter trapped in the monofilament fibres. For comparison reasons and to address the technical challenges involved in DFG recycling, the same type of input material was used for all trials.

Fig. 3.1: Gillnet-dominated input material as retrieved at sea and after shredding. © Andrea Stolte

3.1 Thermal processing

3.1.1 Pyrolysis

Pyrolysis of polymers was conducted at 500-700°C in the laboratory pyrolysis oven in the *Unit of Technology of Fuels (Technologie der Energierohstoffe TEER)* at the Technical University of Aachen (RWTH). The solid residue contained a large ash and coke fraction, implying that depolimerisation leads to a solid residue of about 66% of the input material weight at the comparably low temperatures used in pyrolysis reactors. Higher-temperature techniques such as steam reforming operating at temperatures above 1000°C with a high humidity level (see below) allow for almost-complete vaporisation and conversion of organic material inlcuding polymers into carbon-binding emission gases (CH_4, CO_2). Pyrolysis operates at too low temperatures, pressures and with dry material input which does not allow for vaporisation of the carbon content. The coke and ash residue requires further extraction of lead and metals for metal recycling.

One strong argument for pyrolysis brought forth in the context of marine litter is that the liquid condensate could potentially be used as ship engine fuel to sustain operations in the high seas. In our trials, the condensate return was very low with fractions of only 2-5% of the total input by weight. At lower temperatures of 500-600°C, the condensate had a wax-like consistency rendering it unpourable and hence unusable as fuel without prior heating, as is the case for crude oil. The condensate had the lowest viscosity at the highest temperature of 700°C and the required pourability for use as fuel without a prior heating stage. In its denser and more viscous form, the condensate may resemble crude oil, and vessel engines running on crude oil might be able to cope with such a fuel input. However, the chemical composition of condensate originating from mixed input materials is expected to contain contaminants and might not fulfil even the less restrictive DIN regulations for ship engine fuels.

The chemical composition was not tested for further conclusion on using condensate from DFG as engine fuel, and the return was still low at higher temperatures resulting in a fuel fraction of at most 5% of the input weight.

A possible further limitation of pyrolysis in mixed polymer samples and especially in the case of DFG is the fact that PA6 vaporisation at low temperatures can lead to highly toxic hydrocyanic acid emissions. While toxicity in emissions was not sampled, this limitation might impede the use of pyrolysis in large-scale DFG and marine litter applications. A subsequent gas processing stage can technically remove the toxic content from the pyrolysis gas, but this requires a more complex and expensive system.

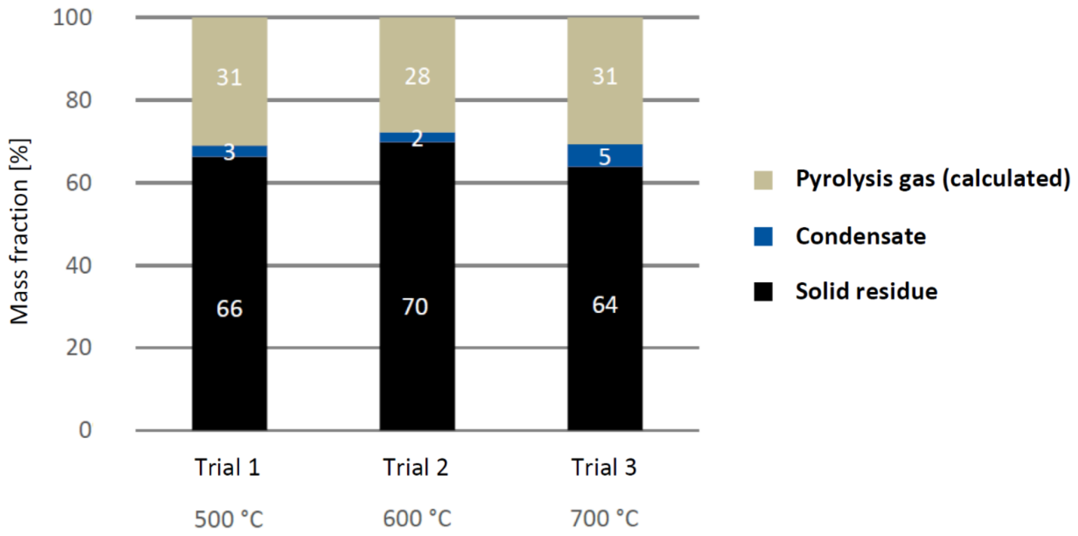

Fig. 3.2: Solid, liquid (condensate), and gaseous output mass fractions of the 3 pyrolysis trials. © TEER | RWTH Thomas Horst, Johann Hee

Fig. 3.3: Condensates from 500, 600, and 700°C pyrolysis trials, respectively. © TEER | RWTH Thomas Horst, Johann Hee

3.1.2 Steam reforming ("hydrolysis")

Steam reforming is a high-temperature vaporisation technique that involves water being split into hydrogen and oxygen atoms in order to generate a synthetic gas with a substantial hydrogen content. The energy contained in polymers or other forms of organic waste is used to split the strong hydrogen bonds of water molecules to generate the synthetic gas. Residual carbon is bound either to oxygen forming CO2 or to hydrogen forming CH4, such that the remaining solid residue contains mostly metal fragments and sediments. A heavily contaminated gillnet sample was processed in EXOY's ultrahigh-temperature steam reforming reactor at 1100°C. The 312kg of gillnet material led to a solid residue of 151kg dominated by sediments and lead. The lead fraction in the residue was more than 42%, implying a lead contamination of at least 20% in the original material. The vaporisation resulted in a synthetic gas with 48% hydrogen content and CO, CO2 and CH4 as the other dominant components. In contrast to lower-temperature pyrolysis where organic molecule disintegration leads to a larger ash and coke residue and the formation of hydrocyanic acid in the presence of polyamide molecules, steam reforming does not result in toxic emissions. The solid residue has virtually no coke content and is composed mainly of steel/iron powder, re-condensed lead fragments, residual sediments, and a small amount of sludge. Because of its melting and recondensation and the low coke residue, lead can easily be extracted for recycling, hence avoiding gillnet-dominated DFG having to be disposed of as hazardous waste. The synthetic gas can be exploited either for direct energy generation through a turbine or as a source of hydrogen for fuel cells. With a hydrogen fraction 10-20 times increased as compared to natural gas, hydrogen extraction should be highly efficient from the resulting synthetic gas. In the case the synthetic gas cannot be exploited or combusted, the CH4 content as a strong greenhouse gas has to be captured to avoid negative effects as a climate change driver if this technique is used on industrial scales.

Fig. 3.4: Solid residue: magnetic dust with iron content (left) and recondensed lead fragments (right). © EXOY

Recommendations on thermal processing

Hydrolysis is recommended for DFG processing when materials are mixed and lead and/or organic contamination is high. Extraction of lead allows for metal recycling rather than depositing DFG as hazardous waste. The hydrogen-rich synthetic energy gas generated from polymer disintegration provides a more efficient form of energy-reuse of DFG polymers than heat extraction in a classical thermal waste incineration plant. Additional benefits of steam reforming are the low processing effort and costs. Only pre-extraction of large metal and rock items is required prior to shredding to 20-30mm fibre length. More elaborate processing stages such as density separation or fibre washing are not necessary prior to thermal processing.

3.2 Material recycling

Material recycling of density-separated and washed fibres was attempted for the same gillnet-dominated samples used as input for thermal processing experiments. The required efforts in terms of further processing steps and manual labour could therefore directly be compared. The experiments were carried out at the Water and Circular Economy Resources Centre of the Technical University of Magdeburg-Stendal. The chemical and mechanical analyses confirmed the results by the external polymer laboratory (Sec. 2). Mechanical properties suggest the polymer components could be material recycled under the prerequisite that a better separation and washing technology can be developed. Residual fine-grained sediments were observed to cause extensive wear on cutting and grinding equipment. Material recycling of gillnet-dominated samples proved very challenging because of the residual contamination with lead and wood fragments, sediments, and the overall polymer mix. The dominant material PA6 was mixed with PET, PP and PE disturbances. The polymer mix implies a wide range of melting points from 140 to 260°C. Less thermally stable low-density polyolefins PP and PE would begin to coke at the temperatures required to melt and regranulate PA6 and PET. The resulting recyclates would contain ash, leading to a brittle output material. Hence extrusion with the mixed gillnet polymer material cannot be recommended. At Hochschule Magdeburg-Stendal, the fibres were fine-ground to different lengths and exposed to additional washing and density separation experiments. Friction washing had also not been capable of removing tiny lead fragments with up to 2-3mm sizes trapped in small, fluffy PA6 fibre compounds. In addition to lead, small wood and organic fragments are also trapped as a consequence of the structure of the shredded gillnet material that contains loops and knots even when fine-ground down to a grain size of 1mm. In order to evaluate the regranulation potential further, the material was hot-pressed into plates. On these plates, black rubber was identified as a new source of contamination. This rubber contamination can either originate from washing trials carried out in the friction washer before running the DFG trials, or from the DFG itself, e.g. from cable coating that could not be entirely removed. The heated rubber formed porous sections that rendered the pressed plates unstable in these areas. The porous gaps impede production of goods because they provide pre-defined breaking points.

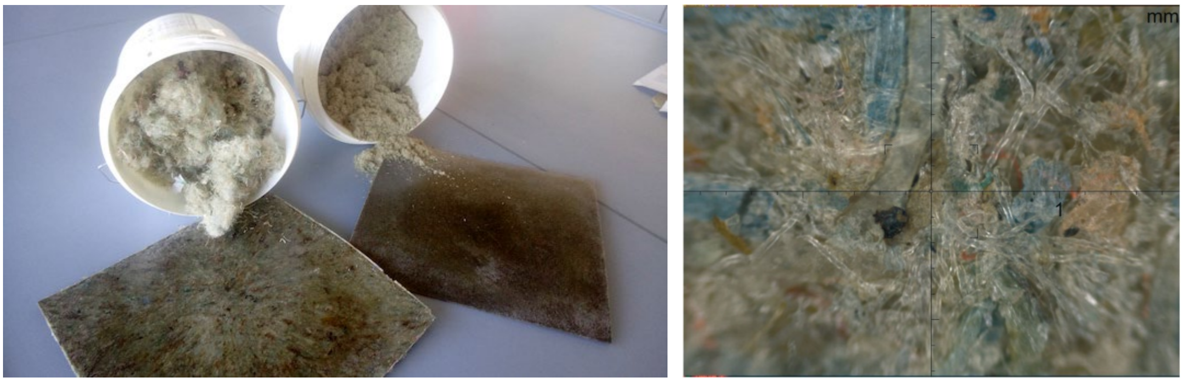

Fig. 3.5: Plates hotpressed from gillnet fibres showing the inhomogeneous structure of the input material. A rubber fragment stands out in the input material near the centre of the microscopic image (right). © Weißbach & Gerke 2018

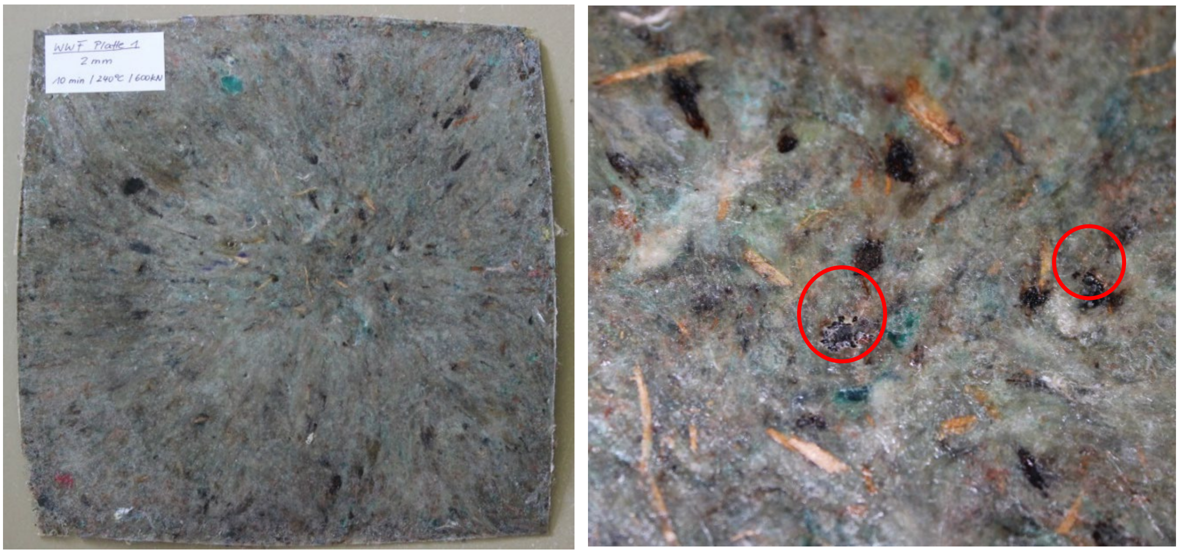

Fig. 3.6: Left: Plate pressed from gillnet fibre material. Right: Microscopic analysis of the pressed plate reveals strong inhomogeneities and that the surface is not closed because rubber inclusions cause porous breaking points. © Weißbach & Gerke 2018

Both rubber and lead contamatination will also be problematic in any extrusion and injection moulding process. A high lead fraction leads to a high toxicity and renders gillnet-dominated DFG unsuitable for material recycling into consumer goods. Rubber contamination leads to breaking points that undermine the material stability desired in polymer products.

Fig. 3.8: Microscopic view of fibres for material recycling trials: Gillnet sample fibres shredded to 20mm grain size at 20x magnification (left), to 1mm grain size at 100x magnification (middle), grinding to 0.08mm led to coking of the less thermally stable polymers as evidenced by the grey colour in the fine-ground sample (right). All grain sizes retained loops and knots impeding clean material separation. © Weißbach & Gerke 2018

In summary, the following obstacles to material recycle were encountered in the case of gillnet-dominated DFG samples:

- A high degree of residual contamination with sediments, lead, and organic matter (> 37% by weight)
- Complex multi-component material mix containing at least 4 types of polymers
- Knots, loops and twists are retained down to very small grain sizes of less than 1mm
- Contamination with wood and rubber fragments prohibits uniformity
- Material mix is expected to result in inhomogeneous melts
- Diversity in polymer melting points results in coking of least thermally stable polymers
- Recyclates are expected to have a high degree of brittleness and fracture points
- Lead is spread during processing throughout the samples introducing toxicity

The following minimum requirements can be given as recommendations for gillnet material processing:

- Lead lines have to be removed prior to any processing, in particular prior to shredding and washing of the fibres
- Removing visible contaminants is highly beneficial
- Identifiable different material types should be manually separated
- Lower-density and higher-density polymers have to be separated to avoid technical problems during material extrusion

The material recycling trials showed that gillnet-dominated samples are most difficult to recycle despite the comparably pure polyamide net material. Extensive pre-processing including removal of swim- and sink-lines and trapped waste such as cables would be required to allow for polymer recycling. Even with extensive pre-processing, fine-grained sediments and the fluffy consistency of ground PA fibres might impede material recycling.

Recommendations

For gillnet-dominated, entangled DFG, thermal processing will be more efficient in most cases and is therefore recommended. This situation is different for end-of-life gillnets. As fishermen systematically remove swim- and sink-lines for re-use, the net material is well-suited for recycling as nets are composed of the high-value polymers PA6 and PET. End-of-life fishing nets, while not part of the MARELITT Baltic project and recycling trials, are already recycled into yarn, e.g. by Ecoalf in Spain or Aquafil in Slovenia. The Chilean company Bureo regranulates fishing nets to produce skate boards and other beach items. The Danish company Plastix also hosts a small re-granulation unit for PA6 materials. These efforts, although not directly addressing DFG, support the value chain for gillnets which might help to avoid losses from harbour collection sites into the marine environment.

It has to be noted that recycling of DFG or end-of-life fishing gear does not automatically imply a contribution to the maritime circular economy. This is only the case when the resulting recycling products are designed to have a high recycling potential again after their life span.

4. Conclusions

- The mechanical properties of DFG polymers are comparable to recyclates, and hence suited for recycling.
- Recycling starts at the harbour: Pre-processing is key to prepare DFG for recycling.
- The chemical composition allows for material recycling if materials can be separated during pre-processing. Hazardous substances need to be removed.

- Preparation of DFG for material recycling is technically challenging and elaborate, which leads to high costs for both manual labour and machinery.
- Material recycling is most challenging for gillnet-dominated DFG because of lead contamination from sink lines.
- Large trawl net fragments and ropes provide the easiest recycling samples as they are more readily separated from trapped marine litter such as large metal items, rocks and cables. They also provide more uniform materials that might be used in small-scale production series.
- Thermal processing is recommended for DFG heavily mixed with other wastes and contaminated with lead. Especially for contaminated materials, steam reforming is found to be the best option to exploit the polymer energy content to generate synthetic gas and extract lead for metal recycling.

Given the effort required to recycle DFG, two requirements are identified:

1. Retrieved DFG needs to be incorporated into the existing waste management infrastructure in fisheries harbours (see also Press 2018).
2. Retrieval and pre-processing effort by fishermen, divers or other professionals needs to be financially supported by municipalities or national authorities to establish a DFG value chain.

Examples where functioning value chains are built around end-of-life fishing gear are the Swedish harbour Smögen where the Nordish Fisheries Association collects, sorts, and pre-processes fishing gear for material recycling, and the system of the Norwegian fisheries directorate where yearly clean-up and sorting actions are in place. While DFG is a more complicated and mixed material than end-of-life fishing gear, a general waste stream for fishing gear is the first step towards material recycling. Implementing waste fishing gear collection in harbours is one of the claims in the recently drafted European plastics directive. The MARELITT Baltic recycling study provides a first baseline for the recycling options for derelict and end-of-life fishing gear.

MARELITT Baltic Workshop on (Lost) Fishing Gear Recycling 11-13. April 2018 in Stralsund.

All companies and partners participating in recycling trials presented their results and technologies. In addition to the four MARELITT Baltic partner countries Estonia, Germany, Poland, Sweden, colleagues working against derelict fishing gear all around the world from Norway, Denmark, the UK, Spain, France all the way to Peru and Hong Kong presented their regional efforts to mitigate the ghostfishing problem.

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The MARELITT Baltic project

Derelict fishing gear (DFG) is addressed worldwide as a source of marine litter with extensive hazardous effects on the marine ecosystem. From 5.500 to 10.000 gillnets and trawl nets are lost every year and despite intense media focus – the problem is poorly known in the fisheries industry and among politicians.

The MARELITT Baltic project is one of the first transnational initiatives in the world to provide an operation oriented all-in-one solution for how to approach DFG. It will turn a diffuse problem into a clear and apprehensible topic that can contribute to an enhanced international readiness to act.

The project is divided into five work packages (WP), where package 2, 3 and 4 are the major parts concerning the cleaning, prevention and recycling of lost fishing gear.

Cleaning the sea and planning future action at sea
The aim of WP 2 is to plan and execute DFG retrievals in Sweden, Estonia, Poland and Germany both on the seafloor and wrecks. The activities will be based on methodologies and techniques tested in earlier national projects. These experiences will contribute to a common methodology which is crucial given the extreme hydrographic and morphological variation in the Baltic Sea. The new operation platform will make cleaning operations both transparent and demonstrate if the task is physically possible.

Responsible fisheries prevention scheme
The aim of WP 3 is to develop an overall approach to mitigate the problem of lost fishing gear in the future. It can roughly be divided into three types of actions. Firstly, the project will increase knowledge on fishing technological and strategic changes over time and how these changes have influenced the evolution of gear loss. In the second step, the project will focus on the potential causes to why fishing gears are lost. The third category of action includes development of preventive methods such as gear marking technologies helping to track irresponsible fishermen or assisting responsible fishermen to locate lost gears.

Marine litter reception facilities and recycling
The aim of WP 4 is to identify the options for a safe and fully sustainable handling and recycling of the lost fishing gear in a circular approach. Within this work package the phase from reaching the harbour through cleaning, sorting, transport until processing of recycling of the nets will be dealt with. The work encloses a variety of approaches such as creating a knowledge baseline about the transnational status and capacities of harbours, waste handling systems and industries in the Baltic Sea countries.

Projectpartners

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