Macromol. Symp. ***152,*** *1–7 (2000)*

Recycling and re-use of polymeric materials; the limited potential of biodegradables

Leen C.E. Struik *, Löwhardt A.A. Schöen
DSM Research
P.O.Box 18, 6160 MD Geleen, The Netherlands

There has been a debate about the recycling of polymer waste for many years. Often, the discussion was mixed-up with political, emotional or even dogmatic arguments. We would like to discuss the rationale behind recycling, a rationale explaining why certain recycling routes are unsuccessful and others successful and giving some idea of the future developments. Only a few sheets are required: the story is really simple, at least in retrospect.

Fig.1 shows the industrial column. Most polymers start with crude oil. The oil goes to refineries and is processed to chemicals or energy carriers (gasoline, fuel oil, etc.) It is important to notice that the streams are dramatically different in size: about 5 % is used to produce polymers, most of the remainder (95 %) is used for energy production (20 times more) . The refineries produce, a.o., naphta. Using crackers, the chemical industry converts this to C2 (ethylene), C3 (propylene), etc.. These products feed the polymerization plants making PE, PP, EPDM-rubber, etc.. These polymers go to the processors producing packaging film, bottles, etc.. Their products go to a variety of industries, using the polymers for the production and packaging of consumer goods. As an example, take a plastic milk bottle. The filled bottles go to the consumer; after drinking the milk, he ends up with an empty bottle and thus produces the waste. What to do with it?

There are many possibilities (upward arrows in Fig. 1). The first is to clean the bottle and send it back to the milk producer; the return system, well known for glass bottles (milk, beer) or for plastic bottles (coke) . The second possibility is to grind the bottle and to work up the material to a granulate that can be re-used by the processors to make new bottles or other plastic products; this work-up often requires remelting and the chemical structure of the polymer remains unaffected. The process, called "mechanical recycling" is very similar

© WILEY-VCH Verlag GmbH, D-69469 Weinheim, 2000 CCC 1022-1360/00/$ 17.50+.50/0

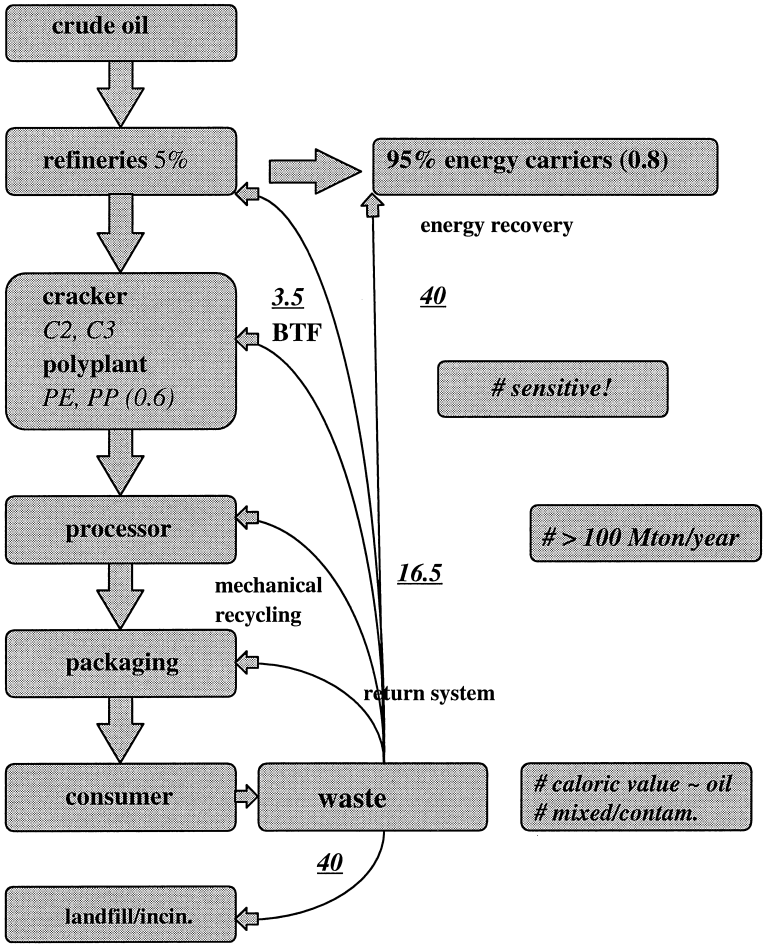

Fig.1: Industry column and possibilities to re-use polymer waste (arrows). Underlined numbers are APME estimates (%) for year 2003 (only recycling, direct re-use not taken into account). In brackets: kg of polymer or fuel from 1 kg of crude oil

to the recycling of glass or metals by remelting.

The third option is to break down the long polymer chains by applying high temperatures either or not in combination with catalysts. Depending on polymer and process conditions, you can return to the original monomers (caprolactam produced from nylon 6 as in the commercial Allied/DSM project), to a naphta substitute (consortium project led by BP after pioneering work by Prof. Kaminsky) or a kind of oil (commercial VEBA process) . These processes are called "back-to-feedstock" recycling (BTF); except for special cases such as nylon 6, these processes plug-in into the cracker or refinery system (see Fig. 1).

The last option is to recover the energy contained in the polymer waste. About 70 % of the total plastic waste produced in Europe consists of polyolefines. Since these polymers have about the same caloric value as fuel oil, the waste can replace oil, coal or gas and thus contribute to a reduction of the consumption of fossile feedstocks.

To develop the rationale, we start with some facts, indicated in Fig. 1 by bold italics:

1. Fact 1 concerns the size: at the moment, the world-wide production of polymers amounts to more than 100 Mton per year; in m^3 more than iron and steel. The investment value of the plants is of the order of 100 billion DM.

2. The second fact concerns the stage of sophistication. We produce 1001 grades, engineered for optimum processability and properties. For example, PE is not a single product: PE stands for a family, one member designed for high-speed film production, the other for super-tough gas pipe, the third for injection moulding of bottle crates, the fourth for making fibres stronger than steel, etc.. These grades are not interchangeable; a good gas pipe can not be made from an injection moulding grade. However, the waste contains a mixture of all these grades. In the past, it has been advocated that mechanical recycling enables the recovery of good products out of this (contaminated) mixture. This idea can be assessed by comparing polymer industry with a master-cook. Industry spent ten thousands of man years to develop the hundreds of polymers and recipes fine-tuned to a large variety of combinations of processing and application; just as the master cook has developed many recipes. Only few people will appreciate the cook mixing-up his recipes at random. Similarly, the idea that mechanical recycling can (economically) recover good products from mixed, contaminated and ill-defined waste gravely underestimates the degree of sophistication of present day polymer technology.

1. Scale + complexity: long replacement time; little help of new (e.g. biodegradable) materials. Waste problem must be solved for existing.
2. Mechanical recycling: particularly monostreams; 10-20 %

3. More options than for glass / metals.

4. No dramatic differences in efficiency (mechanical recycling: 80-90%, energy recovery: 0.6 / 0.8 = 75 %).
No dogmatism.

5. Energy recovery: easier than BTF; plugs-in much larger system

Fig 2: Some conclusions

3. These two points combined immediately show that new materials, e.g. biodegradables can not offer a practical solution to the polymer waste problem (see Fig. 2).The size and sophistication / complexity imply that it will take many tens of years to replace the system. Thus, the waste problem has to be solved for the existing polymers; we cannot wait for the large-scale development of new, e.g. biodegradable polymers. These might be interesting for niche applications but the polymer waste problem is and remains a PE/PP/PVC/PS/PET/etc. problem.
4. Points 1 and 2 also show that mechanical recycling offers an only partial solution of the waste problem. It is useful for the so-called "monostreams", consisting of one particular polymer or a narrow range of polymers. Examples are PVC pipes, super-high impact PP for car-bumpers, PET bottles, etc. If monostreams can be recovered rather easily, mechanical recycling is the preferred option (point 6 below) . However, most polymer waste originates from packaging and is mixed and contaminated; to separate it in useful fractions costs more than the virgin polymers. So, for the majority of the waste, mechanical recycling is not an option. The limits can be estimated by analyzing the composition of the waste: it appears that 10-20% is the maximum. For the rest of the waste, we have to seek other solutions.
5. For polymers, the percentage of waste that is actually recycled is lower than for glass and metals. This is remarkable since the possibilities are considerably greater: metals and glass can not be used to produce energy or other chemical feedstocks.

6. Although the various recycling routes should be compared on the basis of a detailed life-cycle-analysis (LCA) , the following crude estimate is illustrative and useful. From 1 kg of crude oil, we make about 0.6 kg of polymer; 40% is lost (process energy, etc.) in the refinery, the crackers and polymerization plants. Since the polymer has the same heat content as fuel oil, incineration of our 0.6 kg of polymer can save 0.6 kg of fuel oil. To produce this 0.6 kg of fuel oil, we need about 0.75 kg of crude oil. Thus, via the polymer route, 1 kg of crude can be used to enjoy the services of the polymer products and ultimately save 0.75 kg of crude; in other words, the efficiency on the bases of raw materials is of the order of 75 %. This can be compared with mechanical recycling. Here, the waste has to be cleaned, grinded and often remelted and some material is lost. The efficiency is estimated as 80-90 % compared to 75 % for energy recovery. Conclusion: mechanical recycling is the best, but the differences are small. Energy recovery (and similarly feedstock recycling) are next-best options when mechanical recycling is impossible or too costly. There is no ground for the dogmatism of a few years ago: mechanical recycling was almost canonized delaying the development of the other options for several years.

7. The last point concerns the sensitivity to contamination / mixing. As said before, material recycling is very sensitive and limited to clean monostreams; BTF or energy recovery is required for most of the waste. Something that might be unexpected is the following: a cracker is a very large machine ("big animal") consuming something like a Mton of naphta per year. But the big animal is nothing like an omnivore: the requirements imposed on cracker feedstocks are very stringent, e.g. the chlorine should be in the ppm range, some metals in the ppb range, nitrogen very low, etc.. Thus, although big, the cracker is sensitive and critical; feeding with polymer waste gives a lot of problems to be solved. The energy recovery routes are less critical; moreover, the energy stream is 20 times larger. This means that the polymer waste can be diluted in a much larger stream and that the importance of the contaminations can be reduced. We further plug-in into a very large system enjoying all economical benefits of scale. Conclusion: energy recovery is easier and will develop faster than BTF with crackers.

So far for the rationale; it qualitatively explains the prospects of the different routes as published by the European association of plastic manufacturers APME. The numbers (heavy

and underlined in Fig. 1) refer to the year 2003. Only recycling routes are considered, direct re-use of products (return system) is not considered. APME estimates that in 2003, mechanical recycling will recover 16.5% of the waste whilst 3.5 and 40 % will be recycled by respectively back-to-feedstock or energy recovery. The remaining 40 % is incinerated and/or used for land-fill; conventional incineration is distinguished from energy recovery because the energy production is much less efficient, the aim being removal, not energy.
A final remark about the ecological aspects of polymers in general is given in Fig. 3.

- energy / polymers: 95/5
- many polymer products save energy
- example: steel replacement in cars
  - 10 kg plastic→ weight saving of 10 kg
  - 1 % of weight / fuel cons.
  - needed 17 kg of crude
  - savings over 150 000 km → 150 kg of fuel =180 kg of crude
  - × 10 (without recycling)
- similar for many other applications

Fig. 3: Polymers save fossile feedstocks / CO_2 ; essential in sustainable society

About 5 % of the oil is used to produce polymers, the rest goes to energy, e.g. heating of houses, driving of cars, production of steel, etc.. Many polymer products have a diminishing effect on the 95 % stream. If e.g. in cars, steel is replaced by plastics, there is an average weight saving of about a factor of two. This means that 10 kg of plastic replaces 20 kg of steel and reduces the car weight by 10 kg. The fuel consumption is roughly proportional to the weight. With a car weight of 1000 kg, the replacement of steel by 10 kg of plastic implies a weight and fuel saving of 1 %. Suppose our car is used for 150 000 km and has a consumption of 1 kg per 10 km, thus 15 000 kg over its life time. To produce the 15 000 kg of fuel, we need 15 000 · 1.2 = 18 000 kg of crude oil. We save 1 % i.e. 180 kg of crude. To produce the 10 kg of plastic we needed 17 kg of crude. Conclusion: we save ten times more oil than needed to produce the plastic, a multiplier of a factor of 10 (even if we don't recycle the car parts at the end of their service life) . The same applies to many other applications of polymer products, often with higher multipliers. E.g., paints protect steel for corrosion, polymer foams reduce the heat losses by thermal insulation, polymer packaging considerably reduces the loss of food and thus energy required for food production (e.g. fertilizers). Altogether, we think that polymers may very well save more oil than the polymer industry consumes. Abandoning polymers would increase the oil consumption instead of reducing it, i.e. polymers are indispensable in a sustainable society.

Our industry has been criticized severely by ecologists. Since polymers have a positive overall ecological effect, we don't see any reason for a defensive attitude. It must be possible to convince society about this, provided that we complete our "dirty homework" (solve the waste problem).