Characterization of Recycled Injection Molded Plastics for Material Life-Cycle Analysis

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ABSTRACT

This paper describes the effort to develop a methodology for material life-cycle analysis (MLCA). The proposed method seeks to maximize the life-cycle value of an engineering plastic, thereby minimizing costs to society and the environment. The key feature of this method is a standard for performance classification for recycled injection molded plastics. This standard should dictate the maximum amount of regrind and processing conditions required for blending virgin material with regrind of unknown heat histories, and should be easily measurable on-line. This paper describes the experiments that characterize mechanical and rheological degradation of recycled plastics, and the resulting development of a performance classification standard. The paper also summarizes our Product Retirement Compatibility Analysis (PRCA) and its incorporation in an existing computer-based design aid.

1. INTRODUCTION

Background Plastics impact the environment at every stage of their life-cycle: raw material processing, product manufacture, product recycling, reprocessing for new products, and eventually product disposition (Figure 1). The goal of MLCA is to maximize the life-cycle value provided by a material and minimize the costs and impact to the environment, i.e., optimize the material life-cycle strategy. Ideally, a plastic material would not exit the product life-cycle until completely depleted of useful engineering properties; even at this point, any remaining value could be recovered as energy, for example. An effective MLCA strategy requires: 1) information about the behavior of plastic materials as they undergo multiple product life-cycles and, 2) a methodology that incorporates such material knowledge in selecting an optimum material/multi-cycle product scheme.

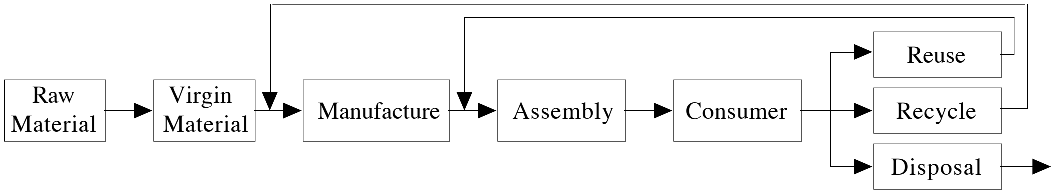


Figure 1: Material life-cycle

MLCA is one domain within product life-cycle design. Life-cycle design is a product design approach that seeks to simultaneously maximize value in all stages of the product life-cycle, including manufacture, assembly, customer use, and disposition. Impending governmental regulations and growing public awareness of environmental concerns has recently placed an emphasis on design for recyclability (DFR). The authors employ a two-tiered approach to DFR: 1) at the system level, facilitate easy separation and disassembly by optimizing the component configuration ("clumping"); and 2) at the component level, choose a material that will satisfy application requirements and permit maximum material life-cycle value recovery. These two goals are coupled, since material choice will impact component compatibility, separation, and disassembly times.

Related Work There has been much recent work in environmentally conscious design and manufacturing. Two broader, system level approaches include Life Cycle Assessment (LCA) and Design for Environment (DFE). LCA is a methodology for identifying environmental burdens that arise from a product or process. The U.S. Environmental Protection Agency [1,2], the Canadian Standards Association [3,4], and the Society of Environmental Toxicology and Chemistry [5] are developing documents that deal with LCA and Environmental Product Design. LCA addresses life-cycle concerns from raw material acquisition to final product disposition. The major challenge of rigorous LCA analysis is the acquisition of the detailed information required. Design for Environment (DFE) is a design philosophy and practice whose goal is to minimize the environmental impact of the manufacture, use, and eventual disposal of products without compromising essential product functions and significantly affecting the life-cycle cost of the product in a negative way [6]. Allenby [7, 8] uses his Design for Environment Information System (DFEIS) to rank various environmental issues pertaining to each life-cycle stage. Glantschnig [9, 10] has done work in DFE at AT&T, focusing on waste minimization during manufacturing and on end of life considerations.

Others have focused on property degradation of recycled plastics. Ries, et. al. [11] studied degradation of polypropylene and found a decrease in impact strength due to a decrease in molecular weight (MW). They suggest that the melt flow index (MFI) can serve as a good predictor of MW, which may allow on-line monitoring of impact strength degradation. Pagel [12] reports that reground ABS resins show very stable physical properties over successive regrind generations, although the resins did show a characteristic yellowing. Zahavich, et. al. [13] has shown that viscosity and swell ratio are the best indicators for degradation of a homopolymeric HDPE resin. Christenson, et. al. [14] found that recycled HDPE is essentially equivalent to virgin HDPE (for a blow/compression-molded household/industrial container-grade resin), although ash content, color and odor did vary. Dzeskiewicz, et. al. [15] showed that mechanical and rheological properties of glass-filled nylon decreased with successive generations, but that generous amounts of regrind can be blended with the virgin resin and still perform according to specification.

Our Approach The focus of this research is to identify an easily measurable material property that correlates with material rheological and mechanical performance. Section 2 describes our Product Retirement Compatibility Analysis. Section 3 details Material Life-Cycle Analysis and an experimental study that explores the feasibility of a material performance predictor for recycled plastics. Section 4 briefly reviews our computerized recyclability analysis, entitled ***LASeR***.

2. PRODUCT RETIREMENT COMPATIBILITY ANALYSIS (PRCA)

Introduction Some DFR guidelines are well established: use uniform materials where possible, permit easy separation of components, place material identification labels in conspicuous locations, use materials with higher recycle demand, etc. However, DFR is often implemented in an ad hoc fashion—companies devise incremental design improvements in response to quickly changing market perceptions or impending governmental regulations. Effective DFR (more efficient resource use at a lower overall cost) requires a systematic approach at the early stages and throughout the design process. Ideally, a systematic approach would provide detailed product, process, and environmental costs as a design progressed from concept to production. This approach would facilitate generation of concept alternatives to produce an optimum balance of product, process, and environmental costs. However, such an ideal is not feasible since the detailed cost models and the information support systems are not yet available. We propose an approach that emphasizes component configuration, or “clumping”. Then, clump compatibility and disassembly costs determine a recycling cost; optimum clumping will minimize the system recycling cost.

"Clumping" Terminology We define a "clump" as a collection of components or subassemblies that share a physical relationship and the same post-consumer intent, such as reuse, recycle, or disposal. Figure 2 shows a system with two groups of compatible materials, and one potential clumping scheme.

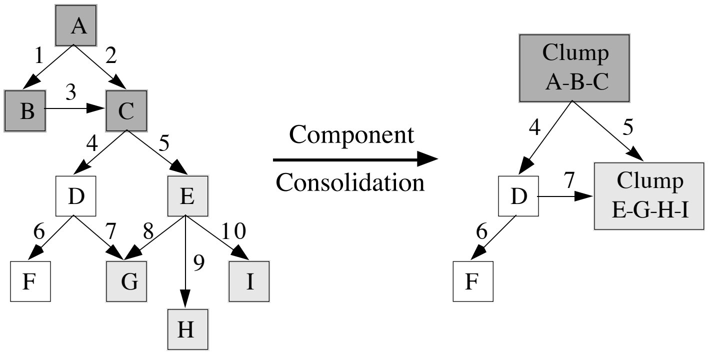


Figure 2: Clumping components with compatible materials

Recycling Cost Model Disassembly and reprocessing costs determine the system recycling cost (Figure 3). For a given system, as the number of individual clumps increases, the disassembly costs rise, and the reprocessing costs fall. Large, complex clumps, while easily removed from the system, require more complex reprocessing techniques. A larger number of simple, homogeneous clumps may require more time to disassemble, but are simpler to reprocess. In our model, material compatibility within individual clumps determines the clump reprocessing cost, and the cost decays exponentially as the compatibility increases (Figure 4). We define perfect compatibility within a clump (compatibility = 1.0) to have zero reprocessing cost, and assign the landfill cost of the clump to 0.2.

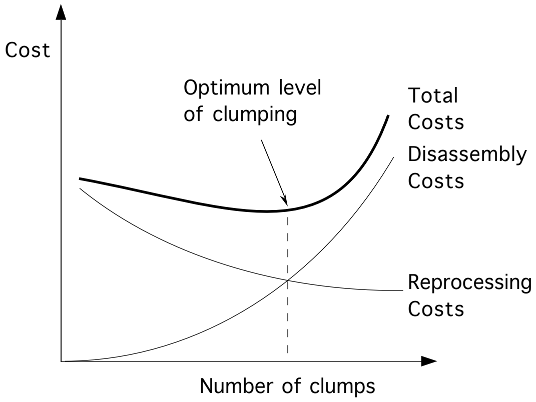


Figure 3: System recycling cost model

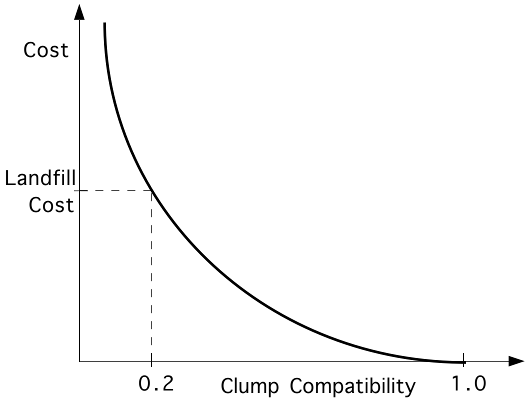


Figure 4: Clump reprocessing cost

3. MATERIAL LIFE-CYCLE ANALYSIS

DFR guidelines place additional requirements on material performance—not only must the material meet the application requirements, but the material should also facilitate compatibility with adjacent components and withstand several product life-cycles. Our current focus is the performance measure for recycled materials with which designers can develop effective recycle strategies. Our intent is not to conduct an exhaustive study of plastics characterization, but to set a standard for material life-cycle guidelines.

Characterization of Recycled Plastics During polymer processing, materials experience thermal and mechanical loadings which produce molecular degradation. Molecular degradation lowers the mechanical and rheological properties of the material. However, adding virgin material to the recycled material can improve its physical, mechanical, and rheological properties. Since the amount of material degradation varies with polymer type and application, engineers require a performance standard for *each* polymer class, based upon on-line rheological properties or measurable quantities. We propose a method with which a designer can specify a target range for mechanical properties (e.g., impact resistance or tensile strength) and through correlation relate to rheological properties measured on-line with a melt indexer (Figure 5). Such a measurement will provide feedback control of virgin/recycling ratio such that the molded part maintains a specified level of mechanical property performance.

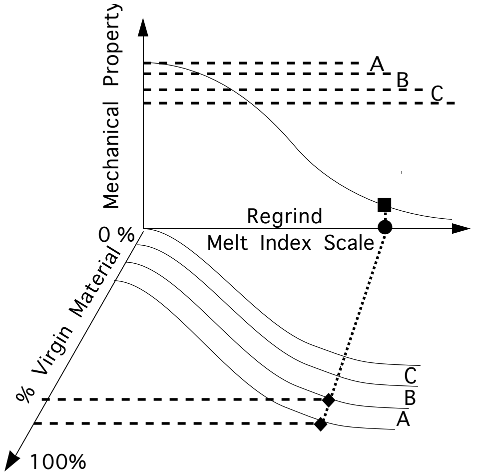


Figure 5: Relationship between mechanical property, melt index, and virgin/regrind mixture

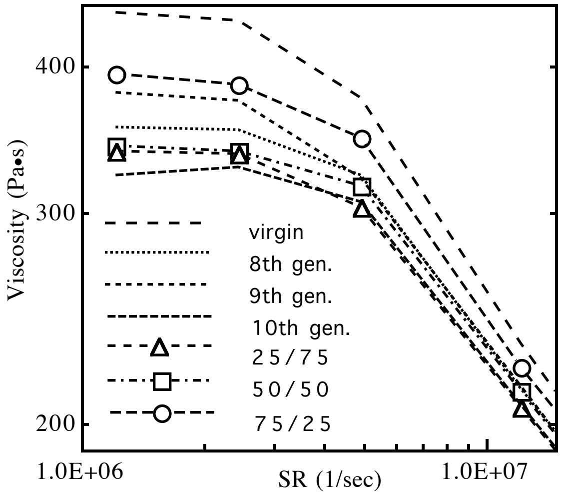


Figure 6: Capillary rheometer results for PC @ 560°F

Experimental Study We are conducting degradation experiments on polycarbonate (PC) and high density polyethylene (HDPE). The study includes two phases: 1) continuously reprocess virgin material until further reprocessing is not possible or until the rheological properties have stabilized; 2) blend different ratios of the degraded material with virgin material. Thus far, we have completed ten process generations of polycarbonate and have blended 75/25, 50/50, and 25/75 virgin/regrind ratios. Response measurements include rheological performance (capillary rheometer, melt indexing, and gel permeation chromatography (GPC)), and mechanical performance (tensile yield strength, Izod and falling dart impact resistance).

Capillary rheometer results for PC are shown in Figure 6. The virgin material initially has a low MW distribution which increases as the material degrades. For this range of shear rates, the difference in viscosity is large enough that the curves do not intersect, yielding more precise melt index readings. Off-site testing of MW and MW distribution using GPC and melt index measurements will provide a better estimate of rheological properties. The preliminary tensile tests show little variation in yield strength or ductility throughout ten generations.

Industry Deployment The melt indexer is a simple and widely-used rheological test, and hence is suitable for on-line property monitoring. However, the melt index is a single point measurement of viscosity at an applied shear rate. Therefore, it is possible to have the same melt index number for materials of different molecular weight distribution (Figure 7). The average molecular weight and molecular weight distribution for each generation, using either solution viscometry or GPC, can reduce erroneous melt index readings. A low shear rate value should be used as a standard for the melt index reading to correspond to shear rates seen through the injection molding process. When rheological curves of different generations intersect, select a standardized shear rate in a region away from the intersection of the curves. To achieve a consistent shear rate from the melt indexer, standardize the applied force, temperature, capillary diameter and length of the testing instrument.

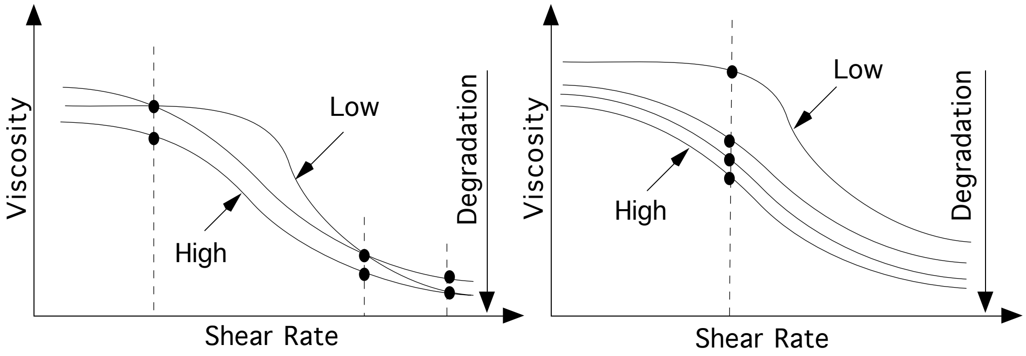


Figure 7: Viscosity curves for materials with different MW distributions

Repeating the rheological and mechanical tests for various ratios will lead to guidelines for the minimum amount of virgin material needed to obtain target performance levels. With the completion of this preliminary study, engineers can specify a target part performance level, rather than specifying specific virgin/ recycle ratios.

4. APPLICATION TO DESIGN TOOLS

The material life-cycle and clumping strategies described thus far led to one module of our life-cycle design tool ***LASeR***: *Linker for Assembly, Service, and Recycling.* The current program is implemented in ToolBook and runs under Microsoft Windows. A common design representation facilitates simultaneous evaluation of several life-cycle domains. The program allows the user to try various strategies for grouping components and evaluates them with respect to assembly, service or recycling. Figures 8 and 9 are screen dumps from the current version of ***LASeR***. Figure 8 shows the Linker design representation for a laser printer paper tray. Figure 9 shows the disassembly cost breakdowns for the paper tray.

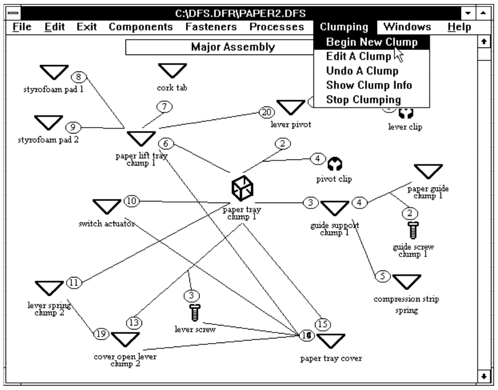
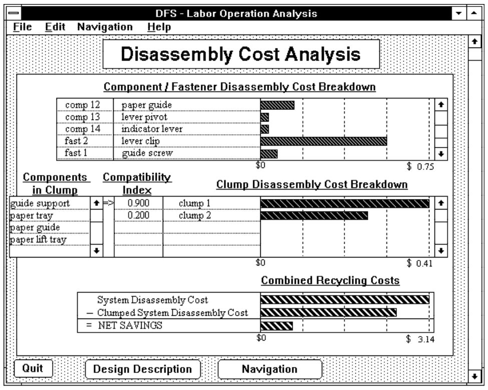


Figure 8: ***LASeR*** linker interface



Disassembly Cost Analysis

Component / Fastener Disassembly Cost Breakdown

comp 12	paper guide	▨
comp 13	lever pivot	▨
comp 14	indicator lever	▨
fast 2	lever clip	▨
fast 1	guide screw	▨

$0 — $ 0.75

Components in Clump		Compatibility Index	Clump Disassembly Cost Breakdown	
guide support	=>	0.900	clump 1	▨
paper tray		0.200	clump 2	▨
paper guide				
paper lift tray				

$0 — $ 0.41

Combined Recycling Costs

System Disassembly Cost	▨
– Clumped System Disassembly Cost	▨
= NET SAVINGS	▨

$0 — $ 3.14

Figure 9: ***LASeR*** recyclability results

5. CONCLUSIONS

This paper reviewed our approach to DFR: optimize component grouping to minimize disassembly costs, and facilitate component material compatibility and material resource recovery by leveraging the material selection process. We presented our current efforts to explore the feasibility of using the melt index as an on-line predictor of material mechanical and rheological performance. Such a measure will allow designers to specify target material properties, instead of specifying virgin/regrind ratios, when incorporating recycled materials into their products. The paper briefly reviewed how material life-cycle analysis is incorporated into a computer program that performs overall recyclability analysis.

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