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Review

Automated sorting of polymer flakes: Fluorescence labeling and development of a measurement system prototype

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ABSTRACT

The extensive demand and use of plastics in modern life is associated with a significant economical impact and a serious ecological footprint. The production of plastics involves a high energy consumption and CO_2 emission as well as the large need for (limited) fossil resources. Due to the high durability of plastics, large amounts of plastic garbage is mounting in overflowing landfills (plus 9.6 million tons in Europe in the year 2012) and plastic debris is floating in the world oceans or waste-to-energy combustion releases even more CO_2 plus toxic substances (dioxins, heavy metals) to the atmosphere.

The recycling of plastic products after their life cycle can obviously contribute a great deal to the reduction of the environmental and economical impacts. In order to produce high-quality recycling products, mono-fractional compositions of waste polymers are required. However, existing measurement technologies such as near infrared spectroscopy show limitations in the sorting of complex mixtures and different grades of polymers, especially when black plastics are involved. More recently invented technologies based on mid-infrared, Raman spectroscopy or laser-aided spectroscopy are still under development and expected to be rather expensive.

A promising approach to put high sorting purities into practice is to label plastic resins with unique combinations of fluorescence markers (tracers). These are incorporated into virgin resins during the manufacturing process at the ppm (or sub ppm) concentration level, just large enough that the fluorescence emissions can be detected with sensitive instrumentation but neither affect the visual appearance nor the mechanical properties of the polymers. In this paper we present the prototype of a measurement and classification system that identifies polymer flakes (mill material of a few millimeters size) located on a conveyor belt in real time based on the emitted fluorescence of incorporated markers. Classification performance and throughput were experimentally quantified using 3 different types of polymers (Polyoxymethylene (POM), Polybutylenterephthalat (PBT) and Acrylonitrile Styrene Acrylate (ASA)) in colored and uncolored form. Overall, 12 classes of plastic flakes were investigated in this study, where 11 classes were labeled with unique binary combinations of 4 fluorescence markers and class 12 includes unlabeled plastic flakes of various colors.

From approx. 68,000 investigated flakes it was found that the developed measurement prototype system achieves an average sensitivity (true positive rate) of 99.4% and a precision (positive predictive value) of 99.5%, while being able to handle up to approx. 1800 flakes per second.

Contents

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1. Introduction

Plastic has become the most common material and hardly any other material influences our daily life as much as plastics do. It has been used in almost every area such as packaging, construction, automotive, electronics, and medicine which results in a steadily growing worldwide demand of approx. 288 million tons in the year 2012 (PlasticsEurope, 2013).

This extensive demand of polymers in combination with the high durability after the rather short product life phases causes significant environmental and economical impacts because the production of plastics is accompanied by a high energy consumption, a significant discharge of CO_2 and it requires a large amount of the fossil resources like crude oil. In order to preserve the world's limited natural resources and reduce the massive flow of plastic garbage to landfills and plastic debris floating in the world oceans (including micro-plastic entering the food chain), polymer recycling has become a high priority from an environmental, economical and legislative point of view. The numbers are quite impressive: just one ton of recycled plastic can save up to 2,604 liters of crude oil, reduce the energy consumption by 80–90% compared to the production of virgin plastics and help to avoid 22 cubic meters of landfill (BIR, 2014). The potential of polymer recycling is thus enormous. In Europe only 62% (15.6 million tons) of plastics were recovered (Plastic Europe, 2013) in the year 2012 while leaving 9.6 million tons for disposal. Most of the plastic waste still occurs in the field of packaging but the electronics sector and the automotive industry are growing producers of post-consumer plastics waste with rather poor recycling rates of approx. 10% (Plastic Europe, 2008).

There is an obvious and urgent need to take a focused and strategic approach towards plastic product and waste management. For example, in order to reduce the many problems with end-of-life products and improve the management of raw resources, the European parliament set up two directives (2000/53/EC and 2002/96/EC) which force manufactures to increase the material recycling rate for end-of-life vehicles to 85% till the year 2015 and for waste electrical and electronic equipment to 80% compared to 2007.

In order to assure a high economical value and an adequate quality of components produced from recycled plastics, a high purity of sorted polymer fractions is mandatory. However, it is difficult in practice to fulfill this requirement since waste polymer streams typically consist of a complex mixture of various plastic types which also may include different kinds of dyes, fillers and additives. Impurities caused by unreliable sorting may lead to phase separation and as a result to structural weaknesses in recycled materials. Moreover, state-of-the-art measurement systems fail to identify black and dark-colored polymers which is problematic especially for the automotive and electronics sector since a large fraction of polymers used there are black. Mid-infrared (MIR) and laser spectroscopy systems are under development and include rather costly hardware components.

A promising way to tackle the existing difficulties in polymer sorting is to make use of a labeling approach based on unique fluorescence dyes (in this article also termed "markers"). These are incorporated into virgin polymer resins during the manufacturing process at the (sub) ppm level and provide specific fluorescence signatures (optical spectra) that allow the recognition (classification) of different plastics. In this article we present the developed measurement system prototype able to identify in real time to which a set of categories individual plastic flakes belong.

This prototype system was developed within a cooperation project of several partners. Singularization and sorting units were developed by an industrial partner. Polymers were provided by an industrial partner as well. The applied fluorescence markers were produced by an academic research center for organic dyes. We developed the measurement system and signal processing for classification purposes.

The classification performance and throughput were experimentally quantified using 12 different classes of plastic flakes (see Fig. 1) of the polymers POM, PBT and ASA in colored and uncolored form. 11 classes were labeled with unique binary code combinations of 4 fluorescent makers and one class did not include any markers at all.

This paper is structured as follows: Section 2 briefly reviews existing automated plastic sorting techniques including their advantages and drawbacks. Section 3 explains the basic idea behind the labeling approach and the use of fluorescence markers for highly reliable plastic sorting. Section 4 focuses on the properties and selection of appropriate fluorescence markers. Section 5 presents the developed prototype system including the hardware and software concepts for the in-line measurement of fluorescence spectra emitted from small plastic flakes carried by a conveyor belt. In Section 6 the experimental setup used to evaluate the classification performance is shown before the achieved results and a brief outlook to future investigations are presented in Section 7.

2. State-of-the-art in plastic classification and sorting

The economical (and environmental) success of recycling polymer materials at the end of their life cycle highly depends on the reliable sorting into different types and grades in an affordable and fast way such that the value of the recycled product exceeds the incurred costs (Niaounakis, 2013; Cornell, 2007). At present, the majority of plastic sorting is still carried out by hand (Niaounakis, 2013) which is slow, very labor intensive and less efficient even if a labeling system such as the resin identification code is applied (Bruno, 2000). Sorting rates of 50 kg/hour until 100 kg/hour are reasonable with a purity of 95% (Pascoe, 2000).