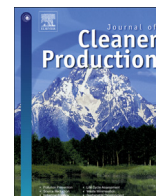




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A review of optimisation techniques used in the composite recycling area: State-of-the-art and steps towards a research agenda

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ABSTRACT

The increased use of carbon fibre and glass fibre reinforced polymer in industry coupled with restrictions on landfill disposal has resulted in a need to develop effective recycling technologies for composites. Currently, mechanical, thermal and chemical approaches have been used to recycle composites. This paper seeks to examine the applications of engineering optimisation techniques in the composite recycling and re-manufacturing processes and their relevant systems, providing an overview of state-of-the-art. This paper is based on a comprehensive review of literature covering nearly all the research papers in this area. These papers are analysed to identify current trends and future research directions. The composite recycling is a relatively new area, and the modelling and optimisation work for composite recycling and re-manufacturing techniques and their relevant systems is still in its infancy. Currently, the optimisation work developed in composite recycling mainly focus on the applications of design of experiments methods. These approaches have been applied to improve the quality of recyclates such as carbon fibres. Some of the soft-computing algorithms have been applied to optimise the re-manufacturing at the system level. Based on the existing research, the area of optimisation for composite recycling and re-manufacturing haven't been well explored despite the fact that many opportunities and requirements for optimisation exist. This means significant amount of modelling and optimisation work is required for the future research. More significantly, considering optimisation at the early stage of a system development is very beneficial in terms of the long term health of the composite recycling industry.

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1. Introduction

In the last 30 years, fibre reinforcement resins, thermoplastics as well as thermosets have been increasingly used in a wide range of applications such as the automotive, aerospace and transportation industries. However, the major drawback of composites is that they are difficult to recycle. This is based on their inherent nature of heterogeneity, especially for the thermoset-based polymer composite (Yang et al., 2012; Ye et al., 2013). The traditional way to deal with the composite waste is disposal in landfills or incineration. These methods are still acceptable due to the relatively low amount of production waste and the fact that most Carbon Fibre Reinforced Composites (CFRCs) produced so far are still in operation. However, the cost of the traditional approaches is high. For instance, the cost

for disposal of CFRCs waste, where not illegal, is around 0.2 GBP/kg (Pimenta and Pinho, 2011). By the year 2030, around 6000–8000 commercial planes are expected to reach their end-of-life (Ye et al., 2013). This will bring a large amount of composite waste. On the other hand, the amount of production waste will increase as the demand for composites and the amount of composites parts produced is growing rapidly. For instance, in Europe and the USA, the annual generation of CFRCs scrap is around 3,000t (Ye et al., 2013). Hence, the demand for developing more cost effective and sustainable composite recycling approaches is growing. Besides future problems with composite disposal, it is also economically beneficial to implement composite recycling. For instance, carbon fibres are an expensive raw material. The price of it as of 2015 is 20 USD/kg. Recycling activities provide the potentiality to use cheap carbon fibres for applications which do not require high strength, and will also ultimately open up new sustainable and secure sources of carbon fibre material. To securely use the recycled carbon fibres, relevant applications and specific standards are needed to be developed (Oliveux et al., 2015a).

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Comparatively, it is easier to recycle thermoplastic matrix composites. Since they can be re-shaped by re-melting and remoulding (Yang et al., 2012). For the thermoset matrix composites, current research on recycling technologies mainly focuses on mechanical (Oliveux et al., 2015a; Howarth et al., 2014), thermal (Pickering, 2006) and chemical recycling (Yang et al., 2012). In the mechanical recycling process, the composites are milled or ground to particles with a length from 10 mm to 50 μm . The thermal recycling processes can combust the resin matrix, thereby recovering the glass or carbon fibres. Chemical recycling uses the dissolution reagents to depolymerise the matrix of composites. Some of these technologies have reached an industrial scale. For instance, the Filon Product Ltd. in United Kingdom use grinding to recycle Glass Fibre Reinforced Composites (GFRCs), ELG Carbon Fibre Ltd. in United Kingdom use pyrolysis, Adherent Technologies Inc. in USA use a wet chemical breakdown of composite matrix resins to recover fibrous reinforcements (Oliveux et al., 2015a) and SGL Carbon in Germany employs a solvolysis process to recycle carbon fibres which can be used in the roof of the new BMW i models and in the rear seat of BMW i3 (Gardiner, 2014; SGL, 2016). The recyclates can be used as filler or reinforcement in new composites. The existing composite recycling techniques have their own advantages and drawbacks. The emerging trend is: mechanical recycling is more suitable for glass fibre reinforced composites while thermal and chemical approaches are more for carbon fibre reinforced composites, since glass fibres are tend to be damaged during thermo-chemical processes (Yang et al., 2012).

The composite recycling is still an immature area. This means the developing techniques mentioned above still need to be optimised to produce higher quality recyclates and improve resource efficiency. Within the existing work, some research focuses on achieving higher quality products in less time. The authors normally try to optimise the recycling techniques with the design of experiment approaches (Meyer et al., 2009; Ye et al., 2013). The basic objective is to find the values of a group of parameters which lead to the optimal decomposition rate and decomposition time. Some other research considers the resource efficiency, energy efficiency for instance, for the aforementioned recycling processes. The existing work of reducing recycling energy consumption has focused so far on searching for more energy efficient operating parameters (Howarth et al., 2014). How to optimally use the recyclates to improve the performance, or reduce the cost of the re-manufactured product is also a very important issue worth investigating. Research works have also been developed focusing on this topic (Meira et al., 2014; Pohlak et al., 2010). Optimisation is important for the development of composite recycling techniques as it can help to improve recyclate quality and process efficiency, as well as reduce cost. Currently, there is no paper focusing on the

state-of-the-art of the applications of optimisation techniques on composite recycling. The aim of this paper is to examine a number of optimisation approaches used in the composite recycling area and outline the future research issues that optimisation in composite recycling as a practice should cover.

This review is done in the framework of the Efficient X-sector Use of Heterogeneous Materials in Manufacturing (EXHUME) project. The purpose of this EPSRC funded project is to establish a sustainable and cost-effective strategy for deconstructing, recycling and remanufacture of composite materials. In the remaining of the paper, the methodology used to deliver this review and the optimisation techniques used in the mechanical, thermal and chemical recycling are presented in Section 2; then, in Section 3, optimisation approaches used at the re-manufacture stage is presented; finally, the research gaps and important research opportunities for the future are proposed in Section 4.

2. Techniques used to optimise the recycling approaches

According to Roy et al. (2008), the engineering optimisation is a process of identifying the right combination of the product and associated process parameters for the best solution. Traditionally, the process is often done manually. The manual approach can be very time consuming, and the searching ability of it is limited and can often lead to sub-optimal solutions. Some automatic searching approaches have been developed in recent decades such as Genetic Algorithms (Holland, 1975) and Swarm Intelligence (Blum and Li, 2008) and offer alternative methods to the more traditional manual approaches. The mathematical modelling for a specific process is normally developed before the application of optimisation techniques. The purpose of this paper is to search the applications of modelling and engineering optimisation in the composite recycling and re-manufacturing areas.

The composite recycling or re-manufacturing system can be studied at different levels. These levels range from the entire factory to the recycling techniques (the y axis in Fig. 1). As shown in Fig. 1, each of these levels has its corresponding optimisation objectives (the x axis). At the recycling techniques level (mechanical, thermal and chemical recycling methods), improving the quality of recyclates, increasing the recycling rate (decomposition rate) and shortening the processing time are the main issues for consideration. At the equipment level, resource efficiency is the main performance indicator to be improved. This means resources consumption such as energy and water need to be reduced for recycling certain amount of composites. Furthermore, at the enterprise level, the trade-off between quality, resource and time within the whole recycling/re-manufacturing system are to be realised. Fig. 1 also presents the potential approaches to realise the optimisation at each level. For instance, at the enterprise level,

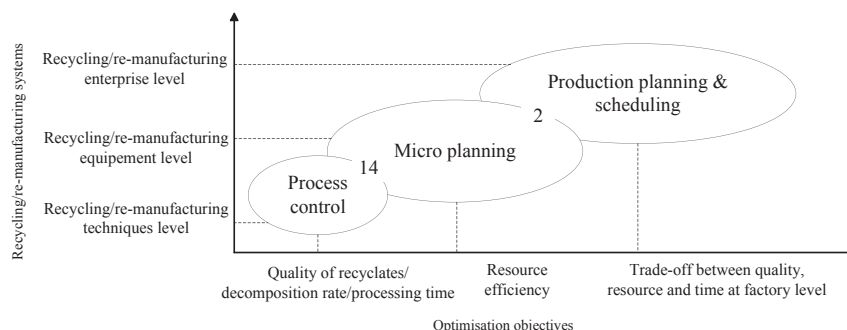


Fig. 1. The levels of composite recycling/re-manufacturing system (based on Vijayaraghavan and Dornfeld (2010)).

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