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Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite

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ABSTRACT

The increased usage of composites in industry coupled with European Union restrictions on landfill disposal has resulted in an urgent need to develop resource efficient recycling technologies. The purpose of this work was to model the electrical energy requirements of milling as a recycling option for carbon fibre composite. By separating the contributions to the total energy required of the machine tool, material cutting energy and material removal rate, the energy demand of carbon fibre composite recycling can be theoretically calculated for any milling process. The model was validated experimentally by comparing the theoretical energy demand to the measured energy demand of an industrial scale milling machine. It was found that at a processing (recycling) rate of 10 kg/hr, the specific energy was significantly less than the embodied energy of virgin carbon fibre (2.03 MJ/kg compared to approximately 200 MJ/kg). Although the form of the recyclate fibres (short, single filaments and bundles) was vastly different to their virgin equivalents (continuous tows), the energy difference highlights the potential environmental benefit of utilising recyclate fibres in place of virgin ones in short fibre composites where mechanical performance is less critical. The relationship between specific energy of recycling and processing rate was also calculated, which highlighted that further energy savings can be achieved at higher processing rates. This work is fundamentally important to provide new data sets for Life Cycle Assessment in order to assess the potential environmental benefits of utilising recyclate fibres.

1. Introduction

The market demand for fibre reinforced plastics (FRPs) has increased massively over the last 30 years with the global demand for carbon fibre reinforced plastics (CFRPs) expected to double between 2011 and 2015 (Witten et al., 2012). The appeal of CFRPs as engineering materials can be attributed to their high specific strength and stiffness, which gives them a considerable advantage over metals especially in non-passive applications such as in the automotive and aerospace industries.

In the UK in 2012, around 134 kilo tonnes of glass fibre reinforced plastic (GFRP) was produced (Witten et al., 2012), along with around 2.7 kilo tonnes of CFRP (Smith 2010). CFRP represents just 2% of the UK composites market by volume but 40% of the value (Smith 2010), thus in terms of recycling there is an economic incentive to recover high value carbon fibres. However the bigger waste problem in terms of volume is with GFRP. These conflicting incentives pose a difficult challenge for research and industry alike in the development of recycling technology. Legislation on disposal to landfill such as the Waste Landfill Directive (1999), combined with industry specific legislation which affects composites such as the End of Life Vehicle Directive (2000) and the Directive on Waste Electrical and Electronic Equipment (2002) have highlighted the need to develop resource efficient recycling technologies for composite materials.

The lack of industrial scale composite recycling needs to be addressed by the industry, both to comply with legislation and become an acceptable waste management solution for the increasing accumulation of waste (both production and end of life). This is a global issue. Recycling technologies, as well as being technologically capable and environmentally beneficial, must be capable of high-throughput.

The aim of this work was to develop and validate on an industrial scale a model for calculating the specific energy demand for milling as a recycling option for waste CFRP. Most Life Cycle Assessment (LCA) software does not have relevant data for recycling of composites. LCAs are important for assessing the environmental impact (and potential benefits) of utilising recyclates, and demonstration of these potential benefits is essential if recyclates

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are to be incorporated into new products as opposed to going to landfill. Witik et al. (2013) stated that the quality of any environmental assessment is strongly dependent on data quality and availability. This highlights the need for accurate resource models. A mechanical process (milling) was chosen as there is machinery on the market capable of processing waste CFRP on an industrial scale. The particular industrial machine for this study was a Wittmann ML2201. As other recycling technologies (pyrolysis, fluidised bed, chemical processes etc.) are developed from pilot plant to industrial scale, resource models for them should also be developed so that the appropriate environmental analyses (typically LCA) can be carried out. Raising the integrity of environmental data is important and critical for supporting sound sustainability decisions.

1.1. Composite recycling methods

The main techniques for the recycling of composite materials can be classified into categories of thermal, chemical, mechanical and radiation based. In thermal recycling, the matrix is separated from the fibres using heat, utilising the different phase change properties of the fibre and matrix phases (Pickering, 2006). Examples of thermal recycling include fluidised bed processing and pyrolysis. The fluidised bed technique has shown promising results; this process recovers relatively clean fibres with little surface contamination (Pickering et al., 2000). In pyrolysis, in addition to fibre recovery, the matrix phase can be recovered as feedstock chemicals. However the surface chemistry of the recovered fibres varies widely according to the processing conditions. Microwave pyrolysis (a radiation based process) is another technique being researched as a possible recycling option for CFRP. A feasibility study carried out by Lester et al. (2004) recovered mostly clean fibres with superior tensile strength retention to a fluidised bed process. Microwave pyrolysis also has the potential to recycle the matrix phase which is recovered as polymer vapour. In chemical recycling, the matrix is separated from the fibres in a reactive medium, for example a super-critical fluid (Jiang et al., 2009). Among the recycling technologies, the most mature technique is mechanical recycling. This technology is important given the waste volumes as it can process at high throughput. There are also potential cross-sector applications for the recyclate, as has been shown for GFRP sheet moulding compound (SMC) waste (Palmer et al., 2009) and pultrusion waste (Meira Castro et al., 2014). A comprehensive review of recycling CFRP for structural applications is given by Pimenta and Pinho (2011). However there is no work that the authors are aware of studying the use of mechanical recyclate from CFRP in non-structural applications. Such an investigation is important as mechanical processes such as milling are technologically the most mature, and thus currently have the best potential to process CFRP waste on an industrial scale. The use of mechanically ground CFRP recyclate could be used as particulate filler in applications such as SMC, anti-static coatings and conductive plastics. Such potential re-manufacture options will be the subject of further work.

1.2. Energy intensity of virgin composite

In the development of process models to be used for LCAs, data for the entire life cycle (cradle-to-grave) must be obtained. Thus in analysis of any product, for the first step the *embodied energy* of the constituent materials must be accounted for. This is the total energy required to produce each constituent material (in the case of composites usually fibres and resins). Table 1 illustrates the embodied energies obtained from literature (Song et al., 2009) of carbon and glass fibres, epoxy and polyester resins (common thermoset matrix phases) and for reference aluminium and stainless steel are included for comparison. The data for aluminium alloys does not differentiate the alloy type; the range of values covers many different types.

Table 1
Embodied energies of common composite constituent materials and 2 common metals (Song et al., 2009).

Material	Embodied energy (MJ/kg)
Carbon fibre	183 to 286
Glass fibre	13 to 32
Polyester resin	63 to 78
Epoxy resin	76 to 80
Aluminium alloys	196 to 257
Stainless steel	110 to 210

It can be seen from Table 1 that carbon fibre material production is significantly more energy intensive than for glass fibre. This is due to the high temperatures required for graphitisation. The embodied energy of the resins is intermediate between glass and carbon fibres. Thus environmentally, recycling of resins may be an area of interest as well.

The next stage in a component life cycle is the manufacturing stage. Fig. 1 shows the energy intensities of the most common composite manufacturing techniques. Compared to carbon fibre manufacture these processes require relatively little energy. As carbon fibre has a relatively high embodied energy, there is greater incentive for recycling technology in terms of energy input, and this combined with their high value makes CFRP recycling an attractive proposition.

1.3. The energy demand model for manufacturing processes

The novel hypothesis for this work is to use specific energy modelling in machining tests and develop mathematical models that can be extended and validated for industrial composite recycling through mechanical milling. The direct electrical energy requirement of the mechanical recycling process was modelled using the energy demand model, Equation (1), developed by Gutowski et al. (2006).

$$E = (P_0 + kQ)t \tag{1}$$

where E is the energy required, P_0 is the power in W consumed by the machine tool, in this case a mechanical recycling machine in the basic and ready to cut state i.e. running at no load, k is the specific energy required for cutting a particular material in Jmm^{-3}, Q is the material removal rate in mm^3s^{-1} and t is the total machining time in s. This model can differentiate between the contributions of the machine tool (process equipment) and the material machinability

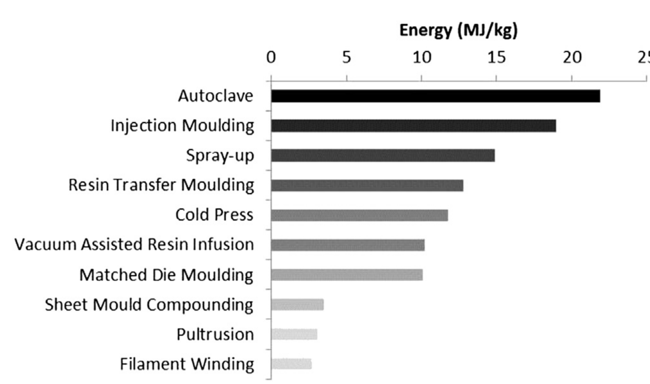

Fig. 1. Energy intensity of composite manufacturing techniques (Song et al., 2009).

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