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High voltage fragmentation of composites from secondary raw materials – Potential and limitations

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ABSTRACT

The comminution of composites for liberation of valuable components is a costly and energy-intensive process within the recycling of spent products. It therefore is continuously studied and optimized. In addition to conventional mechanical comminution innovative new principles for size reduction have been developed. One is the use of high voltage (HV) pulses, which is known to be a technology selectively liberating along phase boundaries. This technology offers the advantage of targeted liberation, preventing overgrinding of the material and thus improving the overall processing as well as product quality.

In this study, the high voltage fragmentation of three different non-brittle composites (galvanized plastics, carbon fibre composites, electrode foils from Li-ion batteries) was investigated. The influence of pulse rate, number of pulses and filling level on the liberation and efficiency of comminution is discussed. Using the guideline VDI 2225 HV, fragmentation is compared to conventional mechanical comminution with respect to numerous criteria such as cost, throughput, energy consumption, availability and scalability. It was found that at current state of development, HV fragmentation cannot compete with mechanical comminution beyond laboratory scale.

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1. Introduction

Higher demand, technological progress and the decreasing lifespan of consumer products lead to challenges for the recycling industry worldwide. Attractive and functional design has to meet price-efficient specifications. The structural elements which need to be recycled are getting more complex and smaller in size. Raw materials tend to become more expensive due to increasing worldwide demand, while compound materials are becoming more and more technologically sophisticated.

At their end of life (EOL), further handling of these products is governed by various legislation, e.g. European Union directive 2008/98/EG concerning waste in general and 2000/53/EG addressing the end of life for automotive products. Apart from the environmental impact, EOL products often contain sufficient valuable matter, which legitimizes even complex technologies for recovery. As a result, the cost of recycling correlates with the complexity of composites (Loehr and Melchiorre, 1996).

In most applications mechanical processes will constitute the first step of recycling, as materials are not yet suitable for metallurgical or chemical processing (Kaya, 2016; van Schaik et al., 2004). Sufficient liberation of the structural elements by comminution is key to their efficient separation into different components. Material liberation is inherently linked to size reduction (Loehr and Melchiorre, 1996). Still, this may not always be true for non-brittle composite materials (van Schaik et al., 2004). For example, size reduction without mechanical disintegration of the material can be achieved through reshaping by plastic deformation or cutting of laminated structures perpendicular to the layers. The energy efficiency and throughput of beneficiation processes typically decreases with decreasing particle size. Liberation should therefore be as high as possible without extensive size reduction. Comminution by high voltage (HV) electric pulses is said to be a promising technology for efficient liberation as stresses mainly occur along phase boundaries (Andres et al., 2001a). This supposedly leads to selective breakage along phase boundaries which inevitably improves liberation at coarser particle sizes (Andres, 2010; van der Wielen et al., 2013).

Besides liberation, energy input, throughput and the robustness of the technology are of importance for its use within a processing plant. Processing cost is mainly driven by energy cost (Napier-Munn, 2015). These costs can be minimized using a proper technology at optimum processing conditions, i.e. considering overgrinding, filling, wet and dry processing, etc. (Napier-Munn, 2015).

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Nomenclature

Symbol			
c_p	specific heat capacity [kJ/K]	N	number of revolutions per second [s^{-1}]
D	degree of liberation [%]	η	efficiency [%]
E	energy [J = Ws]	P	power [W]
f	frequency, pulse rate [Hz = s^{-1}]	Q	heat [J = Ws]
φ	phase angle [°]	T	temperature [K]
I	amperage [A]	t	time [s]
M	torque [Nm]	U	voltage [V]
m	mass [g]	w_r	specific energy input [J/g = 1/3.6 kWh/t]
		x	particle size [mm]

In mechanical processing of secondary raw materials particle shape dominates separation (Friedländer et al., 2006) as the particles are less isometric than in the processing of rocks, ores and coal. This consequently requires a defined modification of particle shape during comminution (Wuschke et al., 2016). Maintaining integrity of the component shape during liberation, as it is achieved by high voltage fragmentation (Dittrich et al., 2016; Martino et al., 2017; Müller et al., 2004), may have positive effects for downstream physical separation. This may also help to prevent the loss of scarce elements, which is typically a corollary during conventional processing, e.g. in shredding plants (Andersson et al., 2017; Bachér et al., 2015).

1.1. Comminution and liberation of non-brittle materials

In comminution, mechanical or thermal energy input leads to the breakdown of bonding forces inside a material. Various physical principles can be used to introduce energy into the material, which have been implemented in machines of different design. Schubert and Bernotat (2004) and Woldt et al. (2004) categorized machines for mechanical comminution of non-brittle materials by the kind of load dominating the process. This scheme now is extended by the authors to take into account mechanical load introduced by shock waves as well as non-mechanical load, such as thermal energy and chemical reaction (Fig. 1).

The classification of machines given in Fig. 1 is based on the type of load the material is being subjected to within the machine. It can be divided into machines utilizing mechanical load and non-mechanical load. The latter one will be thermal energy, e.g. a welding torch. The major part of non-brittle materials is comminuted by mechanical load, typically in machines working with comminution tools. Besides comminution tools, mechanical load can also be introduced into the material by shock waves such as ultrasound or high voltage pulsed power (Andres, 2010; Bluhm et al., 1997).

Taking into account the different working principles and stresses causing fracture, the optimum machinery for the comminution of a non-brittle material can be chosen using the above given classification. The dominating stress in a rotary shear as well as in a translatory shear will be shearing, while in a rotary cutter it is cutting. In rotary shredders the mode of stressing is more complex. It is a combination of tensile stress combined with bending and tearing (Woldt et al., 2004). In case of shock waves, tensile stress is caused inside the material (Duan et al., 2015; van der Wielen et al., 2013).

1.2. Comminution by high voltage pulsed power

As described in the previous section, the energy needed to cause cracking of materials can be introduced with or without the help of comminution tools. The latter one can for example be achieved using high voltage pulsed power. The HV electrical pulse, generated between the electrodes of the machine, moves through the material in the process chamber. Dependent on the rise-time of the electrical discharge, two main principles can be distinguished: when the pulse rise-time is slow, electrical breakdown will happen in the process water (electrohydraulic crushing, EHC); when the pulse rise-time is fast (<10^{-6} s), the electrical breakdown will happen within the solid material (electrodynamic fragmentation, EDF) (Andres, 2010; van der Wielen et al., 2013). The electrical pulse forms a plasma channel which locally introduces high temperature and high pressure (Andres et al., 1999). The shock waves generated by the plasma channel move through the material and cause tensile stresses combined with fracture. Detailed information on the phenomena happening during HV fragmentation can be taken from the referred literature.

Distinct to conventional comminution, where the energy is introduced pointwise or linearly by the comminution tool (Schubert and Bernotat, 2004), the energy input in HV comminution happens directly at phase boundaries (plasma channel) or

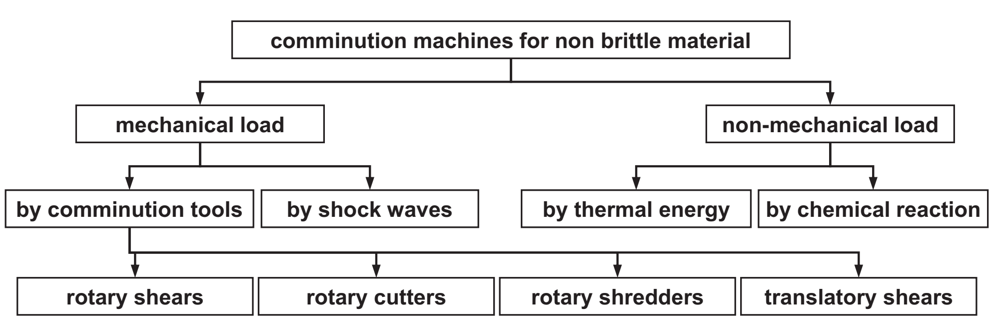

Fig. 1. Process orientated classification of comminution machines based on (Schubert and Bernotat, 2004; Woldt et al., 2004).

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