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Feasibility study of a new approach to removal of paint coatings in remanufacturing

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ABSTRACT

Environmental issues are recognised as being increasingly important, especially in the 21st century; researchers have thus proposed remanufacturing as a means of improving manufacturing sustainability. Cleaning the end-of-life products, that saves commercial values, is one of the most demanding steps and is usually one of the most polluting stages. Product surface coatings, are especially difficult to remove, in this process, because they have been designed to be robust during the service. Traditional methods, aqueous cleaning for instance, are either water consuming or use large amounts of chemical cleaning agents, which are obviously environmentally unfriendly. In this paper, a new approach to removing the paint layers on the surface of the retired product is proposed. The cleaning uses supercritical carbon dioxide ($SCCO_2$) as the pre-treatment, and then wet shot blasting cleaning removes the residues on the treated surfaces. It is difficult to get paint layers in the same condition and the real products are too big for the experimental platform. Experiments were thus carried out using metallic paint sprayed on the steel, with uniform dimensions, mimicking the real paint coatings on the products. The mechanism of $SCCO_2$ treatment was first analysed and specimens treated in different conditions were illustrated. Single-particle shot experiments were afterwards carried out to determine the proper cleaning parameter. The eventual cleaning results using wet shot blasting demonstrated that theoretical analysis was appropriate in this $SCCO_2$ treatment. The resultant cleaning, by use of these two methods, showed satisfactory removal results.

1. Introduction

Remanufacturing, as an industrial practice, is a specific type of recycling in which the end-of-life/used products are returned to like-new or better performance (Bernard, 2011; Liu et al., 2015a). It offers a new approach to recover the functionality of a product, conserving not only the raw material content, but also much of the value added during the processes required to manufacture new products (Giutini and Gaudette, 2003). Steps such as cleaning, disassembly, inspection, reconditioning, test and reassembly are employed in the remanufacturing process. The end-of-life/used products, denoted as cores (Nnorom and Osibanjo, 2010), go through these steps to attain the original performance level (Abdulrahman et al., 2015; Ijomah, 2009) and be equal to the new product warranty (Ijomah et al., 2007). Among these steps, cleaning is obviously one of the most demanding because it directly influences the quality of the subsequent processes, i.e. surface inspection, reconditioning, reassembly and painting treatment (Li et al., 2015).

Contaminant types vary on different cores, e.g. grease, corrosion, scale, carbon deposition and their mixture(Liu et al., 2013). Basically, the cleaning process during remanufacturing removes these contaminants from the cores to the required cleanliness, by mechanical, physical, chemical or electrochemical methods. Coatings, which are artificially coated on the metal products for protection and nice appearance, are one of the commonly observed substances needed to be removed during the cleaning process. This is because that the coatings affect the defect inspection and the condition of reconditioning, hence, impacting the quality of the remanufactured products.

Product coatings are designed to be robust to survive adverse conditions (Chen et al., 2010). Accordingly, the removal of these

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coatings is more difficult to achieve than that of the other contaminants. Research of the coating removal using laser method (Chen et al., 2010; Daurelio et al., 1999), ultrasound (Reinhart, 1989), conventional aqueous cleaning methods (Wolbers, 2000), dry-ice cleaning (Spur et al., 1999) and blasting cleaning (Momber, 2007; Raykowski et al., 2001) has been widely studied.

Each method has associated environmental impacts. During laser cleaning, a focused laser beam combusts paint layers; the small dimension of laser restricts the efficiency of the cleaning process Hazardous gases emitted during laser cleaning are also an inevitable environmental issue when large amount of cores are cleaned. Using organic materials or other chemical removal technologies, aqueous cleaning is considered problematic from an environmental perspective, as it involves various forms of more or less hazardous solvents and detergents (Sivakumar et al., 2009). As dry-ice cleaning sublimates into the atmosphere immediately after the cleaning process, its industrial application aggravates the greenhouse effect. There could be much dust pollution during the conventional blasting cleaning (Balan, 2008), which can probably be harmful to the operators. By adding the water into the shot blasting system, the pollution can be significantly reduced.

In addition, for the end-of-life products, there are usually other organic or inorganic mixtures of contaminant of on the surface or the paint layers, making the situation completed. Our previous studies (Li et al., 2015; Liu et al., 2015a,b) have demonstrated that the combination of supercritical carbon dioxide ($SCCO_2$), as a pre-treatment process, and wet shot blasting, as the removing means, has the feasibility of removal oily contaminant on core surface. When these contaminants are on the paint layer, which is commonly observed, the cleaning situation could be different. Considering that the paint is of organic composition, the feasibility of $SCCO_2$ treatment requires study.

In this paper, the feasibility of this environmental sound combination of the two cleaning methods is studied on the paint layers. Coatings are studied without the existence of other type of contaminants; stainless steel specimens are artificially coated with the metallic paints to mimic the real coatings on the remanufacturing cores. Results from the experiment show results consistent with the theoretical analysis of the mechanism of $SCCO_2$ treatment. Single-particle shot experiments and wet shot blasting cleaning were conducted using the specimens from a previous treatment, illustrating that wet shot blasting cleaning is more effective when accompanied by $SCCO_2$ treatment. Although the efficiency of this process is not yet as high as other methods, this combination of the methods provides an approach to cleaning the paint layers which could prove more environmentally friendly.

2. Mechanism of $SCCO_2$ treatment in paint layers

The presence of a critical point of a pure substance was first discovered by Baron Charles Cagniard de la Tour in 1822 (Berche et al., 2009; Cagniard de La Tour, 1822) and Thomas Andrews named this phenomenon as supercritical (Andrews, 1869) in 1869. A supercritical fluid (SCF) is defined as a substance in the status that temperature and pressure are both over its critical point, as illustrated in Fig. 1. In terms of CO_2, its critical temperature (*Tc*) is 304.128 K and critical pressure (*Pc*) is 7.38 MPa, which is easy to attain under the experiment condition. Currently, the $SCCO_2$ has been widely used for extraction (Lang and Wai, 2001; Marsal et al., 2000; Teberikler, 2001), food processing (Brown et al., 2008; Kinyanjui, 2003), textile processing (Long et al., 2011; Montero et al., 2000), chemical synthesis (Jessop and Leitner, 2008), and cleaning as a solvent (Della Porta et al., 2006; Ramachandrarao, 2006).

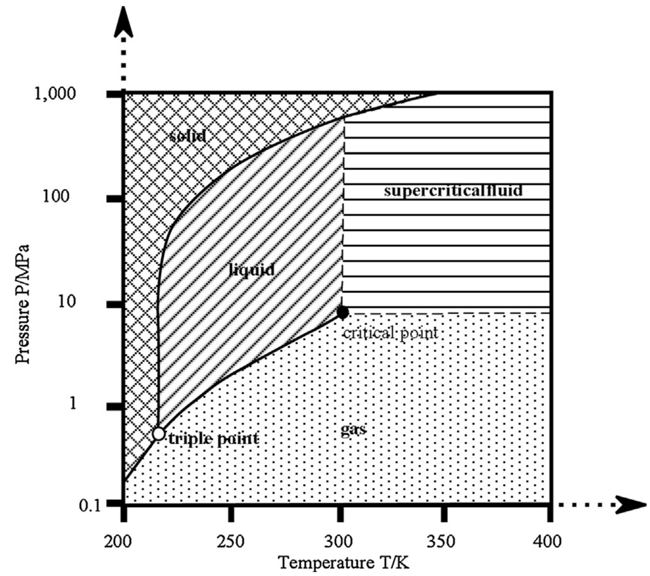

Fig. 1. Temperature-pressure phase diagram of carbon dioxide.

When a substance is in the supercritical status, there is no phase transaction between vapour and liquid. Properties of the SCF can change continuously between gas-like and liquid-like, so that the supercritical fluid presents the properties of both gas and liquid like, including relatively low viscosity, near zero surface tension, high diffusivity and liquid-like density, allowing it to promote mass transfer. Additionally, the operating conditions of CO_2, as aforementioned, are easily attained and relatively benign and CO_2 is non-toxic and non-flammable. It is thus safe to operate paint layer processing using CO_2 in the supercritical status.

$SCCO_2$ has the low viscosity and extremely low surface tension. Consequently, in the supercritical status, the CO_2 molecules diffuse effortlessly into the internal structure of the paint layers. In a certain period of time, the long-chain organic compounds in the layer become porous. This phenomenon has been widely used in the synthesis of porous materials by researchers (Cooper, 2003; Cooper and Holmes, 1999). The foaming theory, describing the behaviour when an organic substrate contacts an SCF, is one of the widely accepted theories and is the main mechanism utilised in the treatment process in this paper. Many models have been established to explain the foaming phenomenon, of which the bubble nucleation theory is widely used (Frayssinet et al., 1998; Goel and Beckman, 1995). In the supercritical condition, CO_2 molecules diffuse inside the polymeric substance becoming a homogeneous system. During the rapid decompression, CO_2 molecules in this system aggregate as a result of the nucleation, developing a tremendous amount of micro bubbles inside the polymer. These bubbles gradually gather and grow bigger until the swelling force reach equilibrium with the resistance, eventually forming cellular structures in the polymer. The walls between two bubbles bear the tensile stress, which is generated during the bubbles becoming bigger. However, the wall may eventually rupture as a result of the expansion of these bubbles; the bubbles, then join together to form a bigger one, as illustrated in Fig. 2.

Based on this theory, the treatment using the $SCCO_2$ can be divided into three processes. Firstly, the CO_2 molecules, in a supercritical condition, diffuse into voids within the paint layer, becoming homogeneous phase with the paint. During the rapid decompression process, CO_2 becomes supersaturated in this homogeneous phase and it is decompressed too fast for CO_2 molecules to escape from the layers; clusters of molecules aggregate into micro bubbles in the paint. Eventually, tensile stresses as a result of