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Environmental benefits of remanufacturing: A case study of cylinder heads remanufactured through laser cladding

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ABSTRACT

Laser cladding is one of the principal means of equipment remanufacturing and the environmental profiles of this technology has become a research focus. This paper examines the environmental impacts of cast iron cylinder head block remanufacturing through laser cladding using life cycle assessment (LCA), and compares it with the new cylinder head block manufacturing. Resource and energy consumptions of each manufacturing and remanufacturing processes are collected along the production line and then the results of six selected environmental impact categories are calculated. Consistency and sensitivity analysis is also conducted after life cycle impact assessment. The results reveal that cylinder head remanufacturing by laser cladding will achieve large environmental benefits, which can cut environment impact over the entire life cycle by 63.8% on average. This paper also discusses the trend of changes in environmental impacts using scenario analysis over different remanufacturing levels. By taking characterized global warming potential (GWP) as the assessment index, the result shows that remanufacturing will no longer be the preferred option if it needs to repair more than 16 cracks by laser cladding for the cylinder head.

1. Introduction

Remanufacturing is an effective way to implement green manufacturing by repairing degraded components and putting the product back into service, thus retaining the value of the extracted and refined materials (Kumar et al., 2007). Due to the adoption of latest technologies, the performance specifications of remanufactured components may achieve or even exceed those of new products from traditional manufacturing (Zhang et al., 2015). On the other hand, from a life cycle perspective, remanufacturing of a product can effectively eliminate a significant portion of the life cycle processes such as raw material acquisition, material processing, machining, etc. which are otherwise all needed for the product development. In this way, remanufacturing can favorably reduce a large portion of resource and energy consumptions as well as environmental emissions.

Due to a high added value and large economic and environmental benefits, automobile components remanufacturing, which shares two-thirds of the industry, has become the research focus in both academy and industry (Steinhilper, 1998). Several reports have recorded the benefits of automobile components remanufacturing, including the manual transmission (Warsen et al., 2011), diesel engine (Smith and Keoleian, 2004; Sutherland et al., 2008; Liu et al., 2014), injectors (Amezquita et al., 1995) and alternators (Schau et al., 2012), all of which indicate that remanufacturing could prolong the product life cycle and in the meanwhile eliminate the overall pollutions compared with new manufacturing. And, compared with other end-of-life strategies, although remanufacturing may cause more impact during the process, it can lead to more environmental benefits from a life cycle perspective (Luglietti et al., 2014). However, as one of the most effective methods to remanufacture the damaged parts, laser cladding remanufacturing can be hardly find in the former research.

The cylinder head is one of the most perishable and complex parts of a direct injection engine. It is used to exchange the air and gas in the cylinder and help to seal the combustion gas under a harsh operation condition: rapidly and repeatedly changing

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working temperature, alternating thermal stress, etc. In addition, the tensile strength and stiffness of its material (usually cast iron) is relatively low. Therefore, cracks are easily found between the value seats of the air inlet and exhaust ports on top of the cylinder head where stresses are highest (Dong et al., 2013). Two options can be considered once the crack appears: (1) discard and recycle the cylinder head, which will not only lead to monetary loss but also bring about serious resource waste and environmental pollution, or (2) remanufacture the cracked cylinder head with a welding repair or laser cladding.

Welding repair will seriously affect the substrate not only because the applied heat can lead to higher residual stresses, but also the weld-seam position is easily susceptible to a secondary crack. Laser cladding, however, has a higher forming accuracy, lower substrate thermal effect zone, and an outstanding mechanical property (Xu et al., 2015). Therefore it can not only overcome the disadvantages of welded repairs but also retain the same quality and performance as that of a new cylinder head (Dong et al., 2013). Due to the advantages of laser cladding, this technique has been widely used into the remanufacturing of the volume damage of the failure parts (Xu, 2007), including cylinder heads (Dong et al., 2013), camshafts (Dong et al., 2011), and turbine blades (Shepeleva et al., 2000; Vilar et al., 2009). However, all of the reports are focused on the effect of input variables (including power, feeding rate and scanning speed) or on output variables (including microstructure, hardness, and surface roughness, etc.). There is no report on the environmental impact of laser cladding remanufacturing, especially when used on metal parts. An objective environmental profile of laser cladding remanufacturing is necessary and still yet to be found.

Due to the characteristics of several powders, some negative emissions may appear during laser cladding processes and result in some adverse environmental impacts. The goal of this paper is to quantify and compare the environmental impact along the entire life cycle of a newly manufactured cast iron cylinder head with its remanufactured counterpart. During the remanufacturing processes, laser cladding with metal powders is utilized for repairing cracks. Life cycle assessment (LCA) method is applied to calculate the accumulated environmental impact of the two manufacturing methods and consistency and sensitivity analysis is also conducted after life cycle impact assessment. Further, this paper tries to conduct GWP of scenario analysis and determine the number of cracks in one cylinder head that can be repaired with laser cladding under the precondition that environmental benefits are ensured. The results of this study can help to provide convincing information when judging the environmental benefit of laser cladding remanufacturing over traditional manufacturing.

2. Material and methods

2.1. Method and database

Life Cycle Assessment (LCA) is a systematic methodology used to identify the cumulative environmental impacts of a product, process, or an activity resulting from its entire life cycle and to identify opportunities for achieving environmental improvements (Basket et al., 1995). Four components are consisted in a typical LCA: (i) Goal and scope definition, providing system boundary and functional unit of product system; (ii) Life cycle inventory analysis (LCI), calculating the consumptions of recourses and energy as well as emissions along with a product life cycle; (iii) Life cycle impact assessment (LCIA), evaluating the environmental impact of the resource extraction and emissions identified in LCI; and (iv) Interpretation, providing conclusions and recommendations to decision makers (ISO 14040, 1997).

The final environmental impacts indicator is calculated by Eq. (1):

$$EI = \sum_{k=1}^{n}\left[V_k \times \left(\frac{\sum_{i=1}^{m} EI_i \times G_i}{R_k}\right)\right] \quad (1)$$

where, EI is the final environmental impact indicator; G_i is the value of the ith substance in the life cycle inventory; EIi is the characterization factor of the ith substance to the kth indicator; R_k is the reference value of the kth indicator; V_k is the weight factor of the kth indicator, m is the number of substance related to the kth indicator, and n is the number of indicators.

The software used in this study is E-balance 2.0 made by IKE Environmental Technology and Sichuan University. The Chinese Core Life Cycle Database (CLCD) embedded in E-balance provides the input/output data of unit processes of Energy, Metal/Nonmetal, Chemicals, Transportation and Waste treatment, reflecting the Chinese average industrial level from 2009 to 2012, excluding the importation (Liu et al., 2010).

2.2. Goal and scope definition

2.2.1. Goal of the study

The goal of this study is to quantify the energy consumption and environmental emissions in the entire life cycle of the newly manufactured engine cylinder head and its remanufactured counterpart produced in a Chinese factory. Then, it compares the two results to assess the potential environment benefits of laser cladding remanufacturing of cylinder heads. Six environmental impacts are presented in this paper: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP) and abiotic depletion potential (ADP). Also, this study will look in detail at all the phases of cylinder head laser cladding remanufacturing to identify the stage with the largest environmental impacts, and help to provide decision making basis for politicians and policy makers who want to promote remanufacturing and applications of new technology.

2.2.2. Functional unit

The cylinder head (material: cast iron, weight: 93.6 kg) with six in-line cylinders from a WD 615.87 diesel engine manufactured in a certain company is selected as the subject of this study. The functional unit is defined as "manufacturing and remanufacturing of two sets of cast iron cylinder heads with the same type".

2.2.3. System boundary

The scopes and boundaries of this study are illustrated in the Figs. 1 and 2. For cylinder head new manufacturing (Fig. 1), the processes include raw material production and transportation and manufacturing; for remanufacturing (Fig. 2), the processes begin with a used cylinder head sent back to the workshop, going through disassembly, cleaning, inspection, refurbishing, and post processing.

In order to simplify the LCA modeling, several simplifications or hypotheses are made as following:

1) Because it is required that the quality and performance of the remanufactured component is equal to the new one, the stages of usage and end-of-life disposal would be the same and then they are excluded from the boundary.