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A Carbon Emission Evaluation Method for Remanufacturing Process of a Used Vehicle CVT Gearbox

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ABSTRACT This paper presented a feasible quantitative method to evaluate carbon emissions of the remanufacturing process of a used vehicle CVT (Continuously Variable Transmission) gearbox. The carbon emission evaluation method is proposed, which is combined with the Hierarchical Relevance Analysis (HRA) theory and the Emission Factor Approach (EFA). In this research, the characteristics of the carbon emissions of remanufacturing process for a used vehicle CVT gearbox are analyzed, various carbon sources on the remanufacturing system are classified and analyzed to define the boundaries of the remanufacturing system, and the correlation matrices among the hierarchical essential factors of carbon emissions are established. Then it combined with EFA to calculate the carbon emissions of each carbon source for the used vehicle CVT remanufacturing process. Finally, the proposed method is experimentally verified by using laser repairing of a used CVT wheel, and the feasibility of new quantitative evaluation method for carbon emissions on the remanufacturing processes is presented. The results show that the carbon emissions of the equipment/device are main contributors of the total carbon emissions of the remanufacturing system. Furthermore, scanning speed of the laser has a significant influence on the carbon emissions of the device and overall carbon emissions of the remanufacturing system.

INDEX TERMS Carbon emissions, CVT gearbox, hierarchical relevance analysis (HRA), laser repairing, remanufacturing process.

I. INTRODUCTION

As the leading industry, the manufacturing industry has a significant value in the process of sustainable development of low carbon manufacturing. The so-called low carbon manufacturing or green manufacturing is aimed at reducing the energy consumption, environmental pollution and carbon emissions [1], and it becomes one of the most important research topics in the modern manufacture industry. It is also well-known that manufacturing is one of the main sources of carbon emissions, the report presented by International Energy Agency (IEA) [2] has shown that manufacturing industries account for nearly a third of the world's energy consumption and 36% of the carbon emissions. Such a high percentage of carbon emissions from the manufacturing industries is significantly amplified the greenhouse effect. Therefore, the development of low carbon manufacturing and remanufacturing process will be an important approach for manufacturing to achieve the goal of energy conservation and emission reduction. In this paper, the remanufacturing process is proposed to improve the utilization of resources and to improve the economic benefits and environmental benefits for the manufacturing industry. The used products on the remanufacturing process are recovered, processed and reused, which conducted by fewer manufacturing procedures and fewer raw materials are used, hence reducing energy consumption and associated carbon emissions [3].

Recently, quantitative research method is widely used to evaluate the carbon emissions from manufacturing processes. Tseng and Hung [4] developed a decision marking model for sustainable supply chain management, where they have considered both the operation costs and social costs of carbon emissions. The results from their research suggested that bearing the social costs of carbon emissions will force the enterprises to reduce carbon emissions. In order to estimate the performance and designing multistage separation

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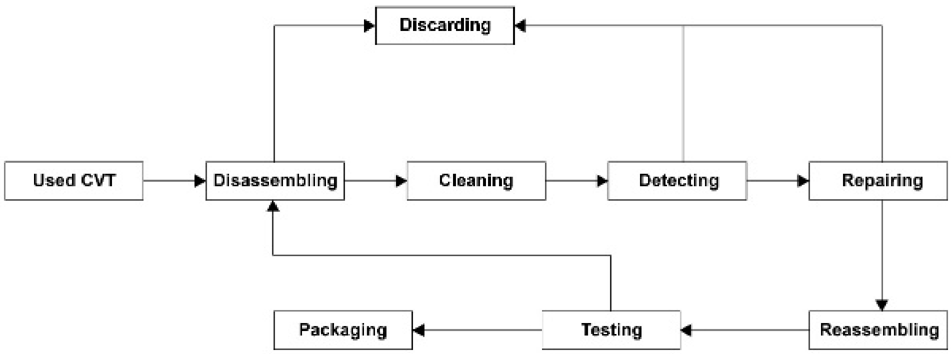

FIGURE 1. Magnetization as a function of applied field.

systems, Wolf *et al.* [5] have studied the resource consumption and environmental impact during manufacturing processes, and a new network flow model for the performance evaluation and the design of material separation system for recycling was presented. The input-output model was first presented by Leontief [6], and it has been extended and applied for environmental input-output models for life cycle analysis to quantitatively calculate the carbon emission of the products for several years [7]–[10] In their research, Jeswiet and Kara [11]. developed a method that connects the electrical energy used in manufacturing to the carbon emissions, and a concept of Carbon Emissions Signature (CESTM) was introduced to evaluate the carbon emissions of the manufacturing process. A machining micro-economic model was proposed by Branker *et al.* [12] to optimize machining parameters and it include all environmental costs and energy consumption. The presented micro-economic machining cost model was based on life cycle analysis (LCA) methodology. Hussain *et al.* [13] quantified the carbon footprint of particleboard products to improve the environmental impacts, where the cradle-to-gate life cycle assessment approach was used. A prediction system proposed by Hirohisa and Hiroshi [14] was used to reduce the environmental burden for a machining operation, and the feasibility of the prediction system was verified by using two Numerical Control (NC) programs to manufacture a simple shape. Moreover, a carbon efficiency approach was presented by Cao *et al.* [15], to quantitatively investigate the life cycle carbon emission of machine tools. Their research proposed improving energy efficiency and optimizing the matching of equipment and production tasks, to reduce various emissions.

Notwithstanding, the literature mentioned above, and some other research on the case study [16]–[20] have provided several methods to evaluate the carbon emissions on the workshop scheduling or different types of machine tools. However, there is limited research focusing on the carbon emissions in the remanufacturing process [21], [22]. There is also little research on the quantitative evaluation method of carbon emissions for the remanufacturing process of a used vehicle CVT gearbox. Hence, the main objective of this research is to propose a new carbon emission quantitative evaluation method for remanufacturing process of a used vehicle CVT. In this paper, a detailed analysis of the remanufacturing process of a used vehicle CVT is presented. Secondly, carbon emission model is created by using the combination of HRA and EFA, to quantitatively evaluate the carbon emissions of the remanufacturing process for a used vehicle CVT. Finally, the proposed carbon emission evaluation method is experimentally verified by using laser repairing/cladding (laser remanufacturing technology) of a used vehicle CVT wheel, and its conduction leads to some useful discussions and conclusions.

II. METHOD

A. REMANUFACTURING PROCESS OF A USED VEHICLE CVT GEARBOX

Remanufacturing is a process of repairing damaged or discarded components/parts, to allow the product performances of the repaired components/parts to satisfy or even exceed new products [23], [24] Recently, it is considered as one of the effective solutions to resource shortage and environmental pollution. The remanufacturing process may be able to achieve the best performance with a minimal input cost. **Fig 1** shows the flow diagram of the remanufacturing process of a used vehicle CVT system. It mainly includes the following processes, they are disassembling, cleaning, detecting, repairing, reassembling and testing. In this section, the analytical description of each process is presented in detail.

Firstly, a used vehicle CVT gearbox is disassembled into several components and parts, the components and parts are carefully inspected along their disassembly process. It is necessary to consider detection results, costs, and the actual conditions together as a whole, to determine the overall replacement, directly utilize or further dismantling repair of the used vehicle CVT system. Besides, the purpose of the cleaning process is to make the components/parts appearance satisfy the requirements of cleanliness of the remanufacturing process. It includes CVT front housing cleaning, dismantled parts cleaning and pre-assembly cleaning. Subsequently, the disassembled and cleaned components/parts are carefully checked by their surface dimension and performance status,

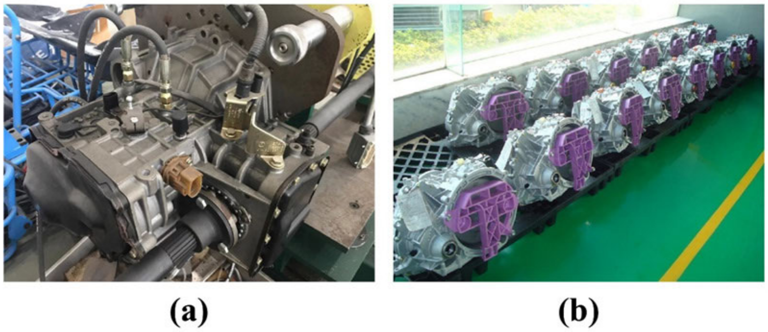

FIGURE 2. Remanufacturing process of a used vehicle CVT system: (a) used vehicle CVT system; (b) reprocessed vehicle CVT gearbox in the laboratory.

TABLE 1. Energy consumption, material consumption and wastes on the used vehicle CVT remanufacturing process.

Remanufacturing processes	Energy consumptions	Material consumptions	Wastes
disassembling	electricity energy, coal, oil, natural gas, *etc.*	tool attrition	waste oil, waste iron, rubber, *etc.*
cleaning	electricity energy, water, compressed air, *etc.*	emery, tool attrition, *etc.*	wastewater, waste emery, waste iron, *etc.*
detecting	electricity energy, water, *etc.*	solvent, tool attrition, *etc.*	waste liquid, waste steel, *etc.*
repairing	electricity energy, water, compressed air, *etc.*	alloy powder, tool attrition, *etc.*	dross, dust, waste liquid, *etc.*
reassembling	electricity energy, lubricating oil, *etc.*	new parts, tool attrition, *etc.*	waste oil, waste steel, *etc.*
testing	electricity energy, lubricating oil, *etc.*	tool attrition, *etc.*	waste oil, dross, dust, *etc.*

to decide either repair or discard the corresponding subassembly components and parts. More importantly, the quality of the repairing process has determined the reusability and performance of the disassembled components and parts. Repair methods of the remanufacturing process, such as brush electroplating, spraying and laser repairing, that have been used and slected are based on the repair requirement of material, thickness, strength, and durability, etc. of the used vehicle CVT. Besides, the repaired components and parts are reassembled (on the reassembling process) into a qualified CVT system in accordance with the technical requirements and product precision. Finally, the remanufactured vehicle CVT gearbox is carefully testing their performance to ensure the gearbox conform to the overall quality requirements. The used vehicle CVT gearboxes and their remanufactured products are shown in **Fig 2**.

Three aspects are mainly contribute to the carbon emissions in the remanufacturing process of a used vehicle CVT. They are the energy consumption, material consumption, and wastes disposal of the remanufacturing process. The energy conversion on the remanufacturing process will produce a large number of carbon emissions, which include the primary energy and secondary energy of the remanufacturing system. Secondly, the carbon emissions are generated during the material preparation of the remanufacturing process, for example, the preparation of a nickel-based alloy in the repairing process will inevitably generate carbon emission. Moreover, the wastes from each process of the remanufacturing process need to be reasonably deal with before into the surroundings, and the waste disposal process will produce a large number of carbon emissions.

The energy consumption, material consumption and wastes of each process of remanufacturing processes of a used vehicle CVT are listed in detail in **Table 1**. It can be seen that the used CVT remanufacturing processes has a complex process, which leads to various energy and material consumption with a large number of carbon emissions. To reduce the wastes and carbon emissions of the remanufacturing process of a used vehicle CVT, it is necessary to develop an appropriate method that can systemically calculate the carbon emission of the used vehicle CVT remanufacturing process.

B. CARBON EMISSION MODEL OF CVT REMANUFACTURING PROCESS

In this section, the system boundaries of carbon emission of a used vehicle CVT remanufacturing process are defined, and the sources of carbon emission are identified, which are based on the characterization of carbon emissions of the used vehicle CVT remanufacturing process. The HRA theory

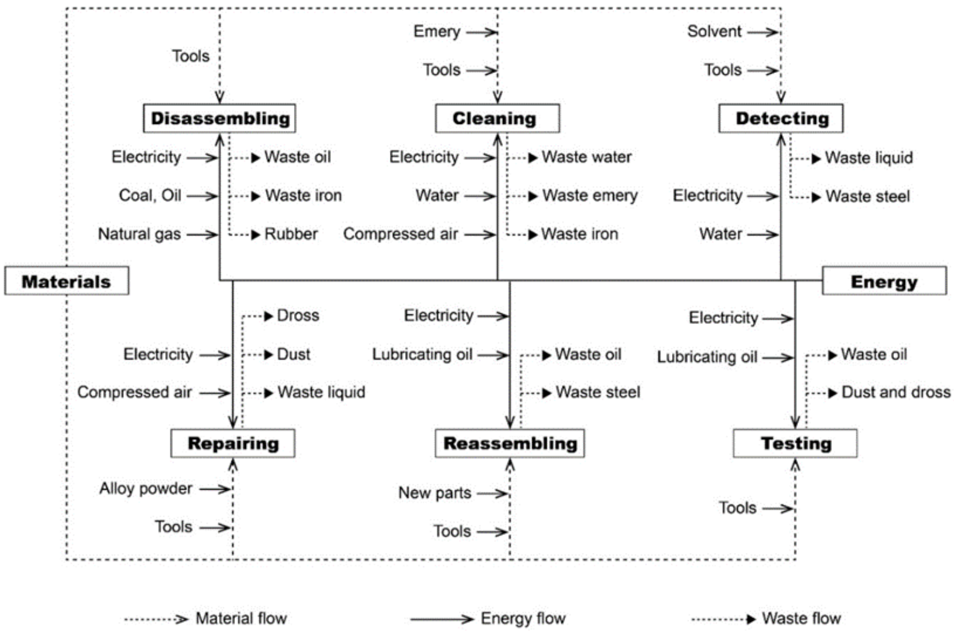

FIGURE 3. System boundaries of carbon emission of a used vehicle CVT remanufacturing process.

is used to sort out the carbon emission factors within the defined system boundaries, and PAS2050 (EFA method) [25] is combined and used to calculate the carbon emissions from each carbon source. Sequentially, a carbon emission model of the remanufacturing process of a used vehicle CVT is established.

1) SYSTEM BOUNDARIES

Fig 3 shows the system boundaries of carbon emission of a used vehicle CVT remanufacturing process. The procedures (including input and output from each process) in the flowchart within the system boundaries are conducted by energy flow, material flow, and waste flow. The energy flow includes the power generated by the equipment and other drive sources. The material flow includes raw material and other auxiliary material input and consumption. The waste flow comprises waste parts, waste liquids and other waste residues from the different processes. It is clear that the energy flow, material flow, and waste flow lead to the flow of carbon emissions within the system boundaries of the remanufacturing process. Furthermore, it can be seen that the electric energy consumption of the equipment, other non-electric energy consumptions, material consumptions, and waste disposal are the four main sources of carbon emission for a used vehicle CVT remanufacturing process.

Generally, it is very difficult to calculate the carbon emissions of remanufacturing process of a used vehicle CVT, and this is due to the fact that the system boundaries are involved in a huge number of parts, components, equipment, materials and various wastes. In order to simplify the system and reduce the computation complexity, a basic unit U is introduced and used to represent the specific parts of the used vehicle CVT system. The four carbon emission sources, partial carbon emission and total carbon emission within the system boundaries are defined according to IPCC (Intergovernmental Panel on Climate Change) [26], and they are defined by the following expressions:

a. Device Carbon Emission (DCE): the carbon emissions generated from the device operating condition (unload or load) of the used CVT remanufacturing process.

b. Energy Carbon Emission (ECE): the carbon emissions produced by the non-electric energy during the preparation process of the used CVT remanufacturing process.

c. Material Carbon Emission (MCE): the carbon emissions generated from the material preparation process of the used CVT remanufacturing process.

e. Waste Carbon Emission (WCE): the carbon emissions produced in the wastes disposal process of the used CVT remanufacturing process.

f. Partial Carbon Emission (PCE): the carbon emissions produced by different assemblies in CVT remanufacturing process are called Partial Carbon Emission, which is used to measure the proportion of different partial assemblies in total carbon emission.

g. Total Carbon Emission (TCE): the total carbon emission produced in the used vehicle CVT remanufacturing process.

As shown in **Table 2**, the carbon emission elements within the system boundaries are divided into six layers by HRA theory. The top layer is total carbon emission, and the lowest layer is the influence factors of carbon emission source. It should be noted that the carbon emission elements in the same layer have the same properties, and they are affected by the lower layer and affect the upper layer.

TABLE 2. The classification and symbol of carbon emission elements in CVT remanufacturing process.

Carbon emission elements	Symbol
total carbon emissions	*TCE*
partial carbon emissions	$PCE_1, PCE_2, PCE_3, \ldots PCE_n$
basic units	$U_1, U_2, U_3, \ldots U_n$
basic carbon sources	*DCE*, *ECE*, *MCE*, *WCE*
processes	$L_1, L_2, L_3, \ldots L_n$
influence factors	$i_1, i_2, i_3, \ldots i_n$

The correlation between different elements in an adjacent layer is different. Therefore, a corresponding correlation matrix is constructed to describe their relational degree. Assume the kth layer ($1 \leq k \leq 5$) contains n elements, and the (k+1)th layer consists of m elements, thus the correlation matrix M^R between the kth layer and the (k+1)th layer can be written as:

$$M^R = \begin{bmatrix} r(1,1) & r(1,2) & \cdots & r(1,j) & \cdots & r(1,m) \\ r(2,1) & r(2,2) & \cdots & r(2,j) & \cdots & r(2,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ r(i,1) & r(i,2) & \cdots & r(i,j) & \cdots & r(i,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ r(n,1) & r(n,2) & \cdots & r(n,j) & \cdots & r(n,m) \end{bmatrix} \tag{1}$$

where $r(i, j)$ is the correlation function between the i th element of the k th layer and the j th element of the $(k+1)$ th layer, their function value is either 0 or 1.

In order to represent the influences of the elements in the same layer acting on the upper layer, the elements in the same layer are respectively compared and to determinate a judgment matrix. By computing the judgment matrix, one we can get the maximum eigenvalue λ_{max} and its corresponding eigenvector W. The normalized eigenvector namely is the relative importance of single-sort weight value of the elements in the same layer to the elements on the upper layer. The evaluation matrix is obtained by combining the rank of all the elements of each layer in the order of high to low and the CVT carbon emission evaluation index. Finally, the correlation of carbon emission impact factors and the total amount of carbon emission is obtained, to determine the effective improvement method for remanufacturing process.

In view of the characteristics of carbon emission in the process of CVT gearbox remanufacturing, the status of different elements in the process of carbon emissions can be identified through the multilevel correlation analysis of carbon emission factors, which contributes to sequencing the quantity of carbon emissions. In order to ensure the rationality of the calculation process and the accuracy of the calculation results, first calculate the specific carbon emissions of basic carbon sources and basic units in the lower layer, then calculate the local carbon emissions and the total carbon emissions layer by layer.

2) CARBON SOURCE MODEL

As shown in **Table 2**, the carbon source model is the fundamental of the carbon emission quantitative evaluation method for remanufacturing process of a used vehicle CVT. The used vehicle CVT remanufacturing includes many processes. Thus the basic carbon source model needs to determinate the correlation matrix between the process and the influencing factor, and combine with the carbon emission coefficient method to calculate the carbon emissions of the carbon sources.

a: DEVICE CARBON EMISSION (DCE)

The processes of a used CVT remanufacturing process are conducted by different equipment, even the same equipment or device used on the CVT remanufacturing process has different working time. Therefore, it is necessary to define the correlation matrix between them. Assume the time correlation matrix M_1^{DCE} between the device and process at unloading running time t_1 is:

$$M^{DCE_1} = \begin{bmatrix} t_1(1,1) & t_1(1,2) & \cdots & t_1(1,j) & \cdots & t_1(1,m) \\ t_1(2,1) & t_1(2,2) & \cdots & t_1(2,j) & \cdots & t_1(2,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ t_1(i,1) & t_1(i,2) & \cdots & t_1(i,j) & \cdots & t_1(i,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ t_1(n,1) & t_1(n,2) & \cdots & t_1(n,j) & \cdots & t_1(n,m) \end{bmatrix} \tag{2}$$

where $t_1(i, j)$ indicates the unload working time of i th device on the j th process. Similarly, the time correlation matrix M_2^{DCE} between the equipment and the process at load working time t_2 can be written as:

$$M^{DCE_2} = \begin{bmatrix} t_2(1,1) & t_2(1,2) & \cdots & t_2(1,j) & \cdots & t_2(1,m) \\ t_2(2,1) & t_2(2,2) & \cdots & t_2(2,j) & \cdots & t_2(2,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ t_2(i,1) & t_2(i,2) & \cdots & t_2(i,j) & \cdots & t_2(i,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ t_2(n,1) & t_2(n,2) & \cdots & t_2(n,j) & \cdots & t_2(n,m) \end{bmatrix} \tag{3}$$

where $t_2(i,j)$ indicates the i th device on the j th process at the load working time t_2. The elementary unit of the device carbon emission DCE can be calculated as follows:

$$DCE = \sum_m^n \sum_{j=1}^m \{[t_1(i,j) + t_2(i,j)] \cdot P_{0i} + t_2(i,j) \cdot P_{1i}\} \cdot E_e \quad (4)$$

where P_{0i} denotes the unload power of the i th device, P_{1i} denotes the load power of the i th device, E_e denotes the carbon emission coefficient of electric energy, and the value is usually $E_e = 0.93$ kgCO$_{2e}$/kWh [27].

b: ENERGY CARBON EMISSION (ECE)

Energy carbon emissions are closely related to the mass dissipation of the energy sources. Thus it is necessary to determinate the mass correlation matrix between the energy and processes of the used CVT remanufacturing. Assume the mass correlation matrix M^{ECE} between the energy and process is:

$$M^{ECE} = \begin{bmatrix} m_1(1,1) & m_1(1,2) & \cdots & m_1(1,j) & \cdots & m_1(1,m) \\ m_1(2,1) & m_1(2,2) & \cdots & m_1(2,j) & \cdots & m_1(2,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ m_1(i,1) & m_1(i,2) & \cdots & m_1(i,j) & \cdots & m_1(i,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ m_1(n,1) & m_1(n,2) & \cdots & m_1(n,j) & \cdots & m_1(n,m) \end{bmatrix} \quad (5)$$

where $m_1(i,\ j)$ represents the mass dissipation of the i th energy on the j th process, and its specific value can be obtained from actual operating conditions. The elementary unit of the energy carbon emission ECE can be calculated as follows:

$$ECE = \sum_{i=1}^n \sum_{j=1}^m m_1(i,j) \cdot E_i \quad (6)$$

where E_i represents the carbon emission coefficient of the i th energy source.

c: MATERIAL CARBON EMISSION (MCE)

Material carbon emission is also closely related to the mass dissipation of the energy sources. Thus it is necessary to determinate the mass correlation matrix between the material and processes of the used CVT remanufacturing process. Assume the mass correlation matrix M^{MCE} between the material and process is:

$$M^{MCE} = \begin{bmatrix} m_2(1,1) & m_2(1,2) & \cdots & m_2(1,j) & \cdots & m_2(1,m) \\ m_2(2,1) & m_2(2,2) & \cdots & m_2(2,j) & \cdots & m_2(2,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ m_2(i,1) & m_2(i,2) & \cdots & m_2(i,j) & \cdots & m_2(i,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ m_2(n,1) & m_2(n,2) & \cdots & m_2(n,j) & \cdots & m_2(n,m) \end{bmatrix} \quad (7)$$

where $m_2(i,\ j)$ represents the mass dissipation of the i th material on the j th process. Similarly, its specific value can be obtained from actual operating conditions. Furthermore, the auxiliary materials (cutting fluid, lubricating oil, etc.) used in the process are related to the operation life, a time standard conversion method is used to convert them into a mass unit, and it is given by:

$$m_{ij} = \frac{T_{ij}}{T_i} \times m_i \quad (8)$$

where m_{ij} denotes the mass consumption of the i th auxiliary material on the j th process, T_{ij} denotes the time of the i th auxiliary material on the j th process, T_i is the standard service life of the i th auxiliary material, m_i is the i th auxiliary material mass consumption. The elementary unit of the material carbon emission MCE can be calculated as follows:

$$MCE = \sum_{i=1}^n \sum_{j=1}^m m_2(i,j) \cdot E_{mi} \quad (9)$$

where E_{mi} represents the carbon emission coefficient of the i th material.

d: WASTE CARBON EMISSION (WCE)

Similarly, the waste carbon emission is closely related to the disposed of mass of the wastes. Thus it also needs to determinate the mass correlation matrix between the waste and the different remanufacturing process. Assume the mass correlation matrix M^{WCE} between the waste and process is:

$$M^{WCE} = \begin{bmatrix} m_3(1,1) & m_3(1,2) & \cdots & m_3(1,j) & \cdots & m_3(1,m) \\ m_3(2,1) & m_3(2,2) & \cdots & m_3(2,j) & \cdots & m_3(2,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ m_3(i,1) & m_3(i,2) & \cdots & m_3(i,j) & \cdots & m_3(i,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ m_3(n,1) & m_3(n,2) & \cdots & m_3(n,j) & \cdots & m_3(n,m) \end{bmatrix} \quad (10)$$

where $m_3(i,j)$ represents the mass of the i th waste generated in the j th process. The elementary unit of the waste carbon emission WCE can be calculated as follows:

$$WCE = \sum_{i=1}^n \sum_{j=1}^m m_3(i,j) \cdot E_{wi} \quad (11)$$

where E_{wi} represents the carbon emission coefficient of the i th disposed waste.

3) CARBON EMISSION QUANTITATIVE EVALUATION METHOD

By determining the carbon emission model of carbon sources and the correlation matrix between the basic unit and the basic carbon source, the partial carbon emission PCE of remanufacturing process of a used vehicle CVT can be calculated as follows:

$$PCE = \left[\begin{pmatrix} r(1,1) & r(1,2) & \cdots & r(1,j) & \cdots & r(1,m) \\ r(2,1) & r(2,2) & \cdots & r(2,j) & \cdots & r(2,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ r(i,1) & r(i,2) & \cdots & r(i,j) & \cdots & r(i,m) \\ \vdots & \vdots & & \vdots & & \vdots \\ r(n,1) & r(n,2) & \cdots & r(n,j) & \cdots & r(n,m) \end{pmatrix} \times \begin{pmatrix} DCE \\ ECE \\ MCE \\ WCE \end{pmatrix} \right]^T \begin{pmatrix} 1 \\ 1 \\ \vdots \\ 1 \\ \vdots \\ 1 \end{pmatrix} \quad (12)$$

where $r(i,j)$ is the correlation function between the i th basic unit and the j th basic carbon source. DCE, ECE, MCE, and WCE represent the Device Carbon Emission, Energy Carbon Emission, Material Carbon Emission and Waste Carbon Emission. It should be noted that the total carbon emission TCE of CVT remanufacturing process consist of many PCE in a different process, and it can be calculated as follows:

$$TCE = \sum\nolimits_{i=1}^{n} PCE_i \quad (13)$$

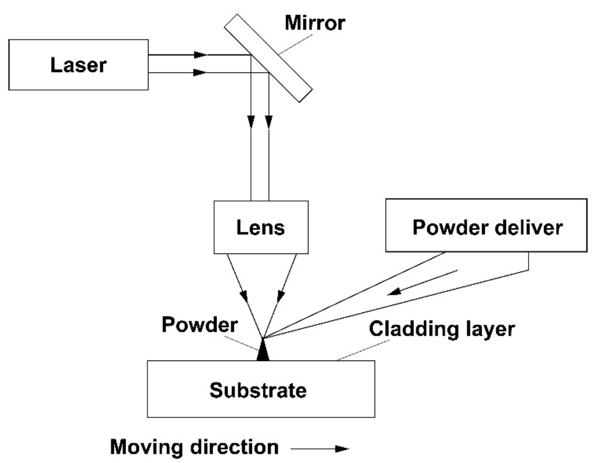

FIGURE 4. Schematic diagram of the synchronous laser repairing method.

III. EXPERIMENT

To verify the feasibility of the proposed carbon emission quantitative evaluation method for remanufacturing process of a used vehicle CVT, an experiment method of using laser repairing of a CVT wheel was presented. **Fig 4** shows the schematic diagram of the synchronous laser repairing method that was used in this study. In this method, a novel high energy laser beam was irradiated to the substrate, in the meantime, the alloy powders were delivered into the melting pool, and they were rapidly melted by the irradiation of the laser. After laser scanning process, the alloy powders were rapidly cooled and solidified to form a repair coating. The repair material used in this experiment was Ni60A + 20% WC alloy powder, which has a particle size of 150 to 325 mesh. The CVT wheel test samples were made of 20CrMnTi, which have an average thickness of 10 mm and a disk diameter of 65 mm. Furthermore, the equipment and devices used in this experiment are an LDF400 semiconductor laser generator, an ABB IRB2400 robotic arm, a Rockwell hardness tester, a linear cutting machine, and an optical microscope.

In this experiment, the surface of the CVT wheel test samples is carefully cleaned up, which was conducted by rust removal and oil removal. The cleaned test samples were then slightly polished on their surface and made corresponding labels. Secondly, the CVT wheel test samples are divided into four groups (named as group a, group b, group c, and group d) with different laser repairing parameters by using orthogonal test method, and each group has three test samples for repairing. It should be noted that the track of the repair should pass the geometric center of the test sample, and its length equals the diameter of the test sample. Fig 5-a shows the laser repairing process of the used CVT wheel test samples. The repaired surface of the test samples was further carefully polished, and their hardness was measured by using a Rockwell hardness tester. Five measurement points were equidistantly selected, and they are avoided the starting and ending points of the laser repairing. Finally, the linear cutting machine was used to cut the test samples that vertically to repair track, as shown in Fig 5-b. After polishing and cleaning the cut cross-section of the CVT wheel test samples, an optical microscope is used to observe the quality of the combined surface of the repaired layer and substrate layer.

IV. RESULTS AND DISCUSSIONS

The vehicle CVT wheel is usually fabricated by 20CrMnTi, its surface hardness can reach 58 $\sim$ 62 HRC after carburizing quenching. The experimentally measured average surface hardness of the CVT wheel test samples on each group with different laser repairing parameters is listed in **Table 3**. It can be seen that the surface hardness of the test samples at all experimental groups are exceeded 55 HRC. In particular, notably, the average surface hardness of the test samples at group b is 58.40 HRC, this means that the surface hardness of the repaired CVT wheel test samples conformed to the hardness requirement of the CVT wheel products. **Fig 6** shows the microscopic structures of the combined interface between the repaired layer and the substratum of CVT wheel test samples. It can be seen that the crystal structure of the repaired layer is relatively good, and even more delicate than the substrate layer. Furthermore, the texture of the combined interface of the test sample from group b is fairly clear, uniform and delicate, it has an excellent combination of repaired layer and substrate layer.

(a) (b)

FIGURE 5. Laser repairing of remanufacturing process of CVT wheels: (a) laser repairing process, and (b) wire-electrode cutting sample.

TABLE 3. The classification and symbol of carbon emission elements in CVT remanufacturing process.

Group	Laser power (*W*)	Scan speed (*mm/s*)	Delivery speed (*g/min*)	Surface hardness (HRC)
a	1500	5	8	57.73
b		6	10	58.40
c	1700	5	10	55.33
d		6	8	55.47

TABLE 4. Parameters of repairing process of CVT wheel remanufacturing (group a).

Processing order	**Equipment model**	P_0 (*kW*)	t_1 (*s*)	P_1 (*kW*)	t_2 (*s*)
rust removing	MT3050	0.6	3	2.4	10
repairing	LDF400	2.5	4	1.5	13
	IRB2400	0.8	4	2.2	13
polishing	MT3050	0.6	3	2.4	10
machining	DK7735	0.5	3	1.5	30

TABLE 5. List of energy, materials and wastes of repairing process of CVT wheel remanufacturing (group a).

Manufacturing procedure	Energy	quantity (*L*)	Material	quantity (*g*)	Waste	quantity (*g*)
dust removing	-	-	emery	0.2	emery	0.2
repairing	compressed air	1.1	alloy	3	steel	1.2
polishing	-	-	emery	0.2	emery	0.2
machining	compressed air	2	cutting fluid	0.3	liquid	0.7
	oil	0.4	tools	0.1	steel	0.1

The proposed carbon emission quantitative evaluation method is applied to calculate the carbon emission of the laser repair process of the CVT wheel test samples. Here, the calculation of carbon emission of the laser repairing of the test sample of group *a* is presented, and is shown as an example in using carbon emission quantitative method to evaluate the carbon emission of the laser repair process. The parameters and data of remanufacturing process of laser repairing of CVT wheel test sample (group *a*) are listed in **Table 4** and **Table 5**, respectively.

Substituting the above mentioned parameters and data into Eq. (2), Eq. (3), Eq. (5), Eq. (7) and Eq. (10), to determinate the time correlation matrix and the mass correlation matrix between the influencing factors and process of laser repairing

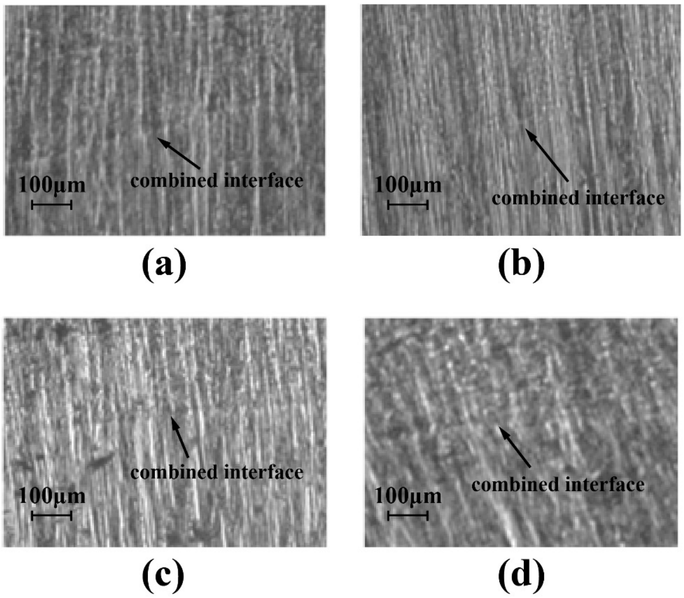

FIGURE 6. Microscopic photography of the combined surface between the repaired layer and substrate layer of the test samples: (a) group a; (b) group b; (c) group c, and (d) group d.

of a vehicle CVT wheel, and gives:

$$M^{DCE_1} = \begin{pmatrix} 3 & 0 & 3 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 0 & 0 & 3 \end{pmatrix} \tag{14}$$

$$M^{DCE_2} = \begin{pmatrix} 10 & 0 & 10 & 0 \\ 0 & 13 & 0 & 0 \\ 0 & 13 & 0 & 0 \\ 0 & 0 & 0 & 30 \end{pmatrix} \tag{15}$$

$$M^{ECE} = \begin{pmatrix} 0 & 1.1 & 0 & 2 \\ 0 & 0 & 0 & 0.47 \end{pmatrix} \tag{16}$$

$$M^{MCE} = \begin{pmatrix} 0.2 & 0 & 0.2 & 0 \\ 0 & 3 & 0 & 0.1 \\ 0 & 0 & 0 & 0.3 \end{pmatrix} \tag{17}$$

$$M^{WCE} = \begin{pmatrix} 0.2 & 0 & 0.2 & 0 \\ 0 & 1.2 & 0 & 0.1 \\ 0 & 0 & 0 & 0.7 \end{pmatrix} \tag{18}$$

By combining Eq. (4), Eq. (6), Eq. (9) and Eq. (11), the device carbon emission (DCE), energy carbon emission (ECE), material carbon emission (MCE) and waste carbon emission (WCE) of the laser repairing of vehicle CVT wheel test samples (group a) then can be calculated as follows:

$$\begin{aligned} DCE &= \sum_{m}^{n} \sum_{j=1}^{m} \{[t_1(i,j) + t_2(i,j)] \cdot P_{0i} + (i,j) \cdot P_{1i}\} \\ &\quad \cdot E_e = 59.24(gCO_{2e}) \end{aligned} \tag{19}$$

$$ECE = \sum_{i=1}^{n} \sum_{j=1}^{m} m_1(i,j) \cdot E_i = 3.06(gCO_{2e}) \tag{20}$$

$$MCE = \sum_{i=1}^{n} \sum_{j=1}^{m} m_1(i,j) \cdot E_{mi} = 31.68(gCO_{2e}) \tag{21}$$

$$WCE = \sum_{i=1}^{n} \sum_{j=1}^{m} m_3(i,j) \cdot E_{wi} = 0.59(gCO_{2e}) \tag{22}$$

The carbon emissions of laser repairing of CVT wheel test samples of group b, group c, and group d are calculated by using the same method, and their results are summarized and listed in **Table 6**.

The results show that the carbon emissions of laser repairing of CVT wheel will changed along with change of the experimental parameters. Compared with other three experimental groups, the total carbon emission of laser repairing of the test samples for group d is minimum, but it has poor repair effect, and the surface hardness of the repair layer of test samples from group d are not satisfy the technical requirements. It should be noted that the laser repairing of CVT wheel test samples of group b has an excellent repair effect, which has the highest surface hardness of the repair layer and its total carbon emission of laser repairing is relatively less than other two experimental groups. Therefore, the laser repairing parameters of group b is more suitable for the laser repairing of a used CVT wheel remanufacturing process. Using the correlation analysis theory to analyze the influencing factors of the carbon emission, and determinate the judgment matrix (shown in **Table 7**) among the carbon emission influencing factors (load power P_1, scan speed v_0, powder delivery rate v_1), it shown as follow:

The maximum eigenvalue of the judgment matrix and the corresponding normalized eigenvector are calculated as follows:

$$W(TCE) = \begin{bmatrix} 0.3108 & 0.4934 & 0.1958 \end{bmatrix}^T \tag{23}$$

$$\lambda_{\max}(TCE) = 3.0536 \tag{24}$$

$$CI(TCE) = 0.0268 \tag{25}$$

$$CR(TCE) = 0.0515 < 0.1 \tag{26}$$

TABLE 6. Carbon emissions of laser repairing of CVT wheel test samples for different experimental group.

Group	Carbon emissions (gCO_{2e})				
	DCE	ECE	MCE	WCE	Total
a	59.24	3.06	31.68	0.59	94.57
b	55.26	2.93	31.68	0.59	90.46
c	59.91	3.06	34.94	0.68	98.59
d	55.82	2.93	28.43	0.25	87.43

TABLE 7. Judgment matrix among the carbon emission influencing factors.

TCE	P_1	v_0	v_1
P_1	1	1/2	2
v_0	2	1	2
v_1	1/2	1/2	1

Through correlation analysis, compared with the laser power among the elements that affect the carbon emissions, it can be seen that the scan velocity has a more significant effect on slowing down carbon emission from equipment or device. The improvement of scan velocity can reduce carbon emission from equipment effectively. Carbon emissions from materials are affected both by the rate of powder delivery and by the scan velocity. Carbon emissions from materials decrease with the reduction of the rate of powder delivery but increase while the scan velocity decreases. Therefore, it is not difficult to draw the conclusion that in the laser repairing process of CVT remanufacturing, carbon emission from the equipment is the most important part compared with other factors of carbon emissions, and the scan velocity has the greatest impact on both the equipment and process of carbon emissions.

V. CONCLUSION

In conclusion, this paper presented a quantitative method to evaluate the carbon emissions of the remanufacturing process of a used vehicle CVT gearbox. It has defined the system boundaries of the remanufacturing process based on the characteristics of carbon emissions of a used vehicle CVT, and various carbon sources on the remanufacturing system are classified and analyzed. The correlation matrices among the CVT parts/components, carbon sources, machining processes and carbon emission influence factors are created by combing of HRA and EFA. A carbon emission model is developed to quantitatively evaluate the carbon emissions of the remanufacturing process of a used vehicle CVT. Finally, the proposed quantitative evaluation method is experimentally verified by using laser repairing of a used vehicle CVT wheel. The results show that the device carbon emission (DCE) is the main carbon emission source of the remanufacturing process of a vehicle CVT. Furthermore, the scan speed has a significant influence on the device carbon emission and the total carbon emission on the laser repair process of a CVT wheel. The future study will focus on the optimization of the laser repair parameters to minimize the carbon emission of the CVT remanufacturing process and ensuring that the quality of the remanufacturing process satisfy technical requirements of the CVT products.

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