Research on used power battery cutting parameters optimization for low carbon and high efficiency

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Abstract—The cutting process of used power battery is a key step for recycling its materials, and it is energy-intensive and high carbon emission process. To reduce the carbon emissions of the used power battery cutting process, the relationship between the carbon emissions of the cutting process and its process parameters was analyzed based on the safety requirements. Next, the multi-objective optimization model for cutting process parameters is established with the goal of minimum carbon emissions and shortest cutting time, which takes into account the constraints of the cutting device's and the safety requirements. For the strong nonlinear characteristics of the optimization model, an improved PSO algorithm is used to solve the model. A case study of cutting a certain type of used power battery is illustrated to verify the validity of the established model.

1. Introduction

As the rapid development of Chinese new energy industry represented by electric vehicles, the disposal of used power batteries has become increasingly urgent [1]. In the process of dismantling used power battery, cutting battery cells is a key step to improve the recovery rate of electrode materials. However, due to the variety of the used battery cells, the economic problems such as improving cutting efficiency are prominent when designing cutting devices, which leads to the high energy consumption and high carbon emission in the process of cutting used power battery cells.

For the safety requirements of cutting, the grinding wheel cutting method is usually adopted to cut the used battery cells for its low-risk compared with laser cutting or water jet cutting. As a special mechanical treatment process, the grinding wheel cutting process of used power battery cell is the process of cutting the cell shell with tool abrasive particles. Therefore, when analyzing the carbon emission of used power battery cutting process, the processes of cutting and grinding can be referred [2]. To reduce the carbon emission of cutting process, Li et al. [3] pointed out optimizing cutting process parameters can significantly reduce the carbon emission of the process. For the great contribution of cutting process energy consumption to carbon emission, Zhou et al. [4] established the relationship between cutting process energy consumption and cutting parameters. For the grinding process, Hu et al. [5] established the optimization model of grinding process parameters aiming at low carbon emission and low cost. Song [6] established the grinding process parameter optimization model with the goal of minimum carbon emission and processing time, which can reduce carbon emission by 30%. Therefore, optimizing the cutting parameters is a key way to reduce the carbon emission of
cutting used power battery. However, the safety requirements are usually not considered in the above researches, while there are strict safety requirements for cutting power battery. Therefore, on the basis of ensuring the safety requirements, the carbon emission sources of used power battery cutting process are analyzed in this paper, and a optimization model aiming at low carbon and high efficiency are established to reduce the carbon emission in used battery cutting process under the condition of minimizing the economic loss.

2. Carbon emission analysis in the cutting process of used power battery considering safety requirements

The structure of the most common square power battery cell is shown in Fig. 1. The disassembly and recycling process are shown in Fig. 2. First, the used power battery cell is fixed as shown in the figure through the fixture b2 on the cutting machine, and then the transmission mechanism drives the tool b4 to move up and down to cut off the electrode head b1 and the underside b3 to expose the electrode material. However, one major problem in above process is that the cutting tool will rub violently and there would be lots of heat generated in the process of penetrating into the cell shell. In addition, when the cutting tool penetrates into the electrolyte in the cell, the positive and negative materials are connected with the electrolyte. At this moment, the cell is in a short circuit state, which further increases the temperature of the cell and results in dangerous consequences, such as gas expansion, smoking, spontaneous combustion or explosion.

As the high chemical activity of the positive material in the power battery cell, the mostly used heat absorbing substances such as lubricating fluid cannot be used in the process of cutting used power battery cells as they can react with cathode materials and reduce the material recovery rate. Therefore, to improve the recovery rate of electrode materials on the basis of ensuring safety, inert substances such as liquid nitrogen are adopted as the coolant in the process of cutting used power batteries [7].

To sum up, when analyzing the carbon emission in the cutting process of used power battery as shown in Fig. 2, in addition to the carbon emission caused by the electric energy consumption of the cutting equipment system $C_e$, it is also necessary to specially consider the carbon emission caused by the consumption of liquid nitrogen $C_n$ and the rapid wear $C_k$ of cutting tools due to lack of lubrication. Therefore, the total carbon emission of cutting used power battery can be expressed as:

$$ C_t = C_e + C_n + C_k $$  \hspace{1cm} (1)

2.1 Carbon emission caused by power consumption

In the cutting process of used power battery cell shown in Fig. 2, the power consumption comes from the cutting equipment and auxiliary system. The power curve of the cutting equipment system in a complete used power battery cutting process is shown in Fig. 3.

2.1.1 Energy consumption of cutting equipment

The energy consumption of used power battery cutting equipment is shown like curve 1 in Fig. 3, which is divided into two parts: no-load stage and cutting stage. The no-load stage refers to when the cutting machine is not loaded, including determining the cutting position $t_{01}$ and separating after cutting $t_{02}$. Liu [8] pointed out that the no-load power of the machine tool, noted as $P_0$ is closely related to the spindle speed $n$, and they show a Taylor series relationship:

$$ P_0 = a_0 + a_1n + a_2n^2 $$  \hspace{1cm} (2)

Where, $a_0, a_1, a_2$ are the parameter related to the working conditions of the cutting machine tool, which can be fitted by historical operation data. Therefore, the energy consumption of cutting equipment in no-load stage can be expressed as:

$$ E_0 = (a_0 + a_1n + a_2n^2)(t_{01} + t_{02}) $$  \hspace{1cm} (3)
Figure 1. Structure diagram of used power battery

Figure 2. Schematic diagram of cutting process of used power battery

Figure 3. Power curve of used power battery cutting process

For calculating the energy consumption of the cutting equipment in the cutting stage, as shown $t_1$ in Fig. 3, the instantaneous power method is selected to calculate the energy consumption of cutting equipment in the cutting stage, as shown Eq (4) [9-11]:

$$E_1 = \int P_1 \times t_1 = \int (F_1 \times v_c \times t_1) = F_1 \times v_c \times t_1$$

(4)

Where, $E_1$ represents the energy consumption of cutting equipment in the cutting stage and $F_1$ is the cutting force exerted by the cutter in the cutting process. $v_c$ is the cutting speed and $t_1$ is the cutting duration, which are calculated by the following formula:

$$t_1 = \frac{as_p}{nf} = \frac{\pi da_sp}{1000fv_c}$$

(5)

Where, $d$ represents the diameter of the cutting tool, and $f$ represents the feed rate. $as_p$ represents the cutting depth.

According to the analysis of the cutting process in reference [12], the cutting force received by the battery cell in the cutting process is related to the cutting speed, cutting depth and feed rate, which form a non-linear relationship:

$$F_1 = \alpha v_c^\beta a_sp^\gamma f^\lambda$$

(6)

Where, $\alpha$, $\beta$, $\gamma$, $\lambda$ are the parameter related to the cutting material and cutting conditions, which can
be determined by the cutting manual.

2.1.2 Energy consumption of auxiliary system
To minimize the possibility of spontaneous combustion caused by heat generated in the cutting process as shown like $t_2$ in Fig. 3, auxiliary systems such as ventilation and heat dissipation are necessary in the cutting process of used batteries. Assuming that the average power of auxiliary device is $P_2$, the energy consumption of the auxiliary system can be expressed as:

$$E_2 = P_2 \times t_2 = P_2 \times (t_{01} + t_{02} + \frac{\pi d a_p w}{1000 f v_c})$$  \hspace{1cm} (7)

2.2 Carbon emission caused by liquid nitrogen consumption
According to the calculation in reference [13], the heat absorption capacity and safety requirements can be ensured by connecting liquid nitrogen when cutting the cell of used power battery. Therefore, liquid nitrogen is considered as the heat absorption material in the process of cutting the cell in this paper. The carbon emission caused by liquid nitrogen consumption can be expressed as:

$$C_n = W_n \lambda_n$$  \hspace{1cm} (8)

Where, $W_n$ is the mass consumed by liquid nitrogen and $\lambda_n$ is the carbon emission factor of liquid nitrogen. According to the energy conversion in the compressed air nitrogen production process, $\lambda_n = 42.09 \text{kg CO}_2 / \text{kg}$. Assuming that the heat generated in the cutting process is absorbed by liquid nitrogen, the mass consumed by liquid nitrogen can be expressed as:

$$W_n = \frac{E_i}{c_p(T_w - T_v) + H} = \frac{\pi d a v^\beta a_p^\gamma f^{a-1}}{1000 [c_p(T_v - T_w) + H]}$$  \hspace{1cm} (9)

Where, $c_p$ is the specific heat capacity of liquid nitrogen, and $T_v$ is the evaporation temperature of liquid nitrogen. $T_w$ is the room temperature, and $H$ is the latent heat of vaporization of liquid nitrogen.

2.3 Carbon emissions caused by cutting tool wear
As there is no lubricating oil, cutting fluid or other substances with lubricating effect adopted in cutting used battery, the wear speed of cutting tools is faster than that of general machining. Therefore, the carbon emission caused by cutting tool wear should be considered in the cutting of used power battery:

$$C_k = \frac{t_k}{T_k} W_k \lambda_k$$  \hspace{1cm} (10)

Where, $T_k$ represents the service life of the cutting tool, and $W_k$ is the weight of the cutting tool while $\lambda_k$ is the carbon emission factor of the cutting tool. For the service life of the cutting tool, it can be calculated according to Taylor's empirical formula:

$$T_k = \frac{m_1}{v_c^{m_2}; a_p^{m_3}; f^{m_4}}$$  \hspace{1cm} (11)

Where, $m_1, m_2, m_3, m_4$ represents the parameters related to tool durability, which can be obtained by referring to the cutting manual [14].
3. Multi-objective optimization model of cutting parameters for used power battery with low carbon and high efficiency

3.1 Optimization objective function

Based on the analysis of the carbon emission sources of the cutting process, the low-carbon and high-efficiency multi-objective optimization model of cutting process parameters are established:

\[
C_r = \xi \left[ (a_0 + a_1 \frac{1000v_c}{\pi d}) + a_2 \left( \frac{1000v_c}{\pi d} \right)^2 \right] \left( t_{01} + t_{02} + \frac{\pi da_{sp}}{1000fv_c} \right) + \frac{\pi d\alpha v_c^\beta a_{sp}^{\gamma+1} f_c^{\lambda - 1}}{1000} + P_t \times (t_{01} + t_{02} + \frac{\pi da_{sp}}{1000fv_c})
\]

\[
t_2 = t_{01} + t_{02} + \frac{\pi da_{sp}}{1000fv_c}
\]

Where, \( \xi \) represents the carbon emission factor of electric energy. Here, \( \xi = 0.35 \).

For the used battery cutting process shown in Fig. 2, the subsequent operation of separating the electrode material from the shell can be carried out only by completely cutting off the battery head and underside. Therefore, the cutting depth is taken as a fixed value in this paper.

For the above optimization model, transform the multi-objective optimization problem into single objective optimization can reduce the difficulty of solution. Therefore, this paper transforms the weighted carbon emission and time-consumed into single objective function for optimization:

\[
\min F(v_c, f) = \min (w_1 C_r^*, w_2 t_2^*)
\]

Where, \( F(v_c, f) \) is the weighted optimization objective function, and \( w_1, w_2 \) are the weight coefficient of carbon emission function and time-consumed function. The normalization method for optimization function adopted in this paper is as follows:

\[
C_r^*(v_c, f) = \frac{C_r(v_c, f) - C_{r_{min}}}{C_{r_{max}} - C_{r_{min}}}, \quad t_2^*(v_c, f) = \frac{t_2(v_c, f) - t_{2_{min}}}{t_{2_{max}} - t_{2_{min}}}
\]

Where, \( C_r^*, t_2^* \) are the normalized functions of carbon emission function and time-consumed function.

3.2 Constraints

3.2.1 Constraints in cutting equipment

In the practical used battery cutting process, due to the limitations of the working conditions of the cutting equipment, the selection of optimization variables would be limited by cutting tool speed, feed rate, maximum cutting force and maximum cutting power:

\[
\begin{align*}
\text{s.t.} & \quad \frac{\pi d n_{min}}{60000} \leq v_c \leq \frac{\pi d n_{max}}{60000} \\
& \quad f_{min} \leq f \leq f_{max} \\
& \quad \alpha v_c^\beta a_{sp}^{\gamma+1} f_c^{\lambda} \leq F_{f_{max}} \\
& \quad \alpha v_c^\beta a_{sp}^{\gamma} f_c^{\lambda} \leq 1000 P_{P_{max}}
\end{align*}
\]
3.2.2 Security constraints
According to the analysis about safety requirements for cutting used power battery, the key point is to avoid the excessive temperature of the battery cell during the cutting process. Therefore, the restriction on the optimization variables should include the restriction on the heat production in the cutting process. According to the summary in reference [13], the ignition point of electrolyte is 403K, which is the lowest among the cell materials of power battery. Therefore, the temperature of used battery cell should not exceed 403K during cutting, as shown in Eq (18).

\[
T_e + \frac{\pi d \alpha v c_m \rho_f}{1000c_m m} \leq 129.85
\]  

(18)

Where, \( c_e \) represents the specific heat capacity of electrolyte, and \( m_e \) represents the mass of electrolyte in battery cell.

3.3 Solution of optimization model based on Improved PSO algorithm
Inspired by the birds' habitat behavior, PSO algorithm solve optimization problem by flying to the center of the group. PSO algorithm can quickly solve the numerical continuity problem as shown in Eq (13). However, most of the constraints in this paper are nonlinear like Eq (18) and Eq (19), and it is hard for PSO algorithm to get out of the local optimal solution. Therefore, an improved PSO algorithm is adopted which introduce shrinkage factor to enhance its local search ability. In the adopted improved PSO algorithm, the velocity and position of particles are updated as Eq (19) ~ (20).

\[
v_i = k \left[ v_i + c_1 \text{rand} \left( \left[ P_i - x_i \right] + c_2 \text{rand} \left( g - x_i \right) \right) \right] \\
x_{i,j}(t+1) = x_{i,j}(t) + v_{i,j}(t+1), j = 1, 2, 3, \ldots d
\]  

(19)

(20)

Where, \( k \) is the expansion factor, which is calculated by the following formula:

\[
k = \frac{2}{2 - \theta - \sqrt{\theta^2 - 4 \theta}}
\]  

(21)

Where, \( \theta = c_1 + c_2 \), and \( \theta > 4 \).

4. Case study
In this section, there is a case about cutting a type of used power battery cell to verify the effectiveness of the high-efficiency and low-carbon multi-objective optimization model of used power battery cutting process established in this paper. The basic information about the used power battery cells and the selected cutting equipment are shown in Table 1.

According to the cutting manual, the tool life coefficient for cutting aluminum alloy materials is shown in Table 2, and other parameters related to calculation are also shown in Table 2.

| Table 1 Basic information about the used power battery and cutting machine |
|-----------------------------|-----------------------------|-----------------------------|
| Information | Explanation | Information | Explanation |
| Shape | Square | Tool size (mm) | 355×3×25.4 |
| Shell material | Aluminum alloy | Tool speed range \([n_{\text{min}}, n_{\text{max}}](m/\text{min})\) | [80, 3900] |
| Electrode material | NCM × Graphite | Tool cutting feed range \([f_{\text{min}}, f_{\text{max}}](\text{mm}/r)\) | [0.5, 3] |
| Size (mm) | 216×134×29 | Maximum cutting force \(F_{\text{max}}(N)\) | 1000 |
| Weight (kg) | 1.45 | Maximum output power \(P_{\text{max}}(kW)\) | 12 |
| Cutting power factor | \(\eta\) | | 0.8 |
Table 2 Calculation parameters

| Model parameters | Value       | Model parameters | Value       |
|------------------|-------------|------------------|-------------|
| $a_0$            | 380         | $c_p$            | 1.083kJ/(Kg·°C) |
| $a_1$            | 1.64        | $H$              | 199kJ/kg    |
| $a_2$            | $2.52 \times 10^{-6}$ | $T_0$        | -196°C      |
| $t_{01}$         | 0.1min      | $W_k$            | 460g        |
| $t_{02}$         | 0.5min      | $m_1$            | 135         |
| $a$              | 90          | $m_2$            | 3           |
| $\beta$          | -0.2        | $m_3$            | 0.75        |
| $\gamma$         | 0.98        | $m_4$            | 0.5         |
| $\lambda$        | 0.85        | $c_e$            | 1.619kJ/(Kg·K) |
| $P_2$            | 1.5kW       | $m_e$            | 0.154kg     |

To verify the effectiveness of the improved PSO algorithm, the calculation result of standard PSO algorithm is introduced to compare. The parameters in the standard PSO algorithm are set as following: $c_1 = c_2 = 1.49445$; Number of iterations $Maxgen = 200$; Population size $sizepop = 200$; Particle update speed $v_{max} = 1$, $v_{min} = -1$. In the improved PSO algorithm, $c_1 = c_2 = 2.05$. The curve of the optimal solution varying with the iterative algebra is obtained after Matlab operation, as shown in Fig. 4 and Fig. 5. Compare Fig. 4 with Fig. 5, it can be seen that the improved PSO algorithm reaches the optimal solution in generation 67, while the standard PSO algorithm reaches the optimal solution in generation 122. The improved PSO algorithm can accelerate the solution efficiency and avoid getting into the local optimal solution.

In Fig. 5, the optimal fitness of the optimization objective function is 0.336. The cutting speed and feed rate under optimal condition are $v_c = 165.3m$ / min and $f = 1.32mm / r$. The carbon footprint and consumed time under optimal condition can be calculated as $C_f = 0.93kg$ and $t_2 = 0.74min$. Before parameters optimization, the parameters of the cutting machine tool for used power battery were determined by manual experience, which were $v_c = 150m$ / min and $f = 1mm / r$. The comparison of carbon emission and consumed time are shown in Table 3. It is demonstrated that the carbon footprint of the cutting process is reduced by 8.6% and the time consumption is reduced by 10.8% after high efficiency and low carbon optimization.
Table 3 Effects comparison of two kinds cutting parameters

|                    | $v_c$ | $a_w$ | $f$  | $C_i$ | $t_2$ |
|--------------------|-------|-------|------|-------|-------|
| Before optimization| 150   | 29    | 1    | 1.01  | 0.816 |
| After optimized by the presented model | 165.3 | 29    | 1.32 | 0.93  | 0.740 |

5. Conclusion
To reduce the carbon footprint of the cutting process of used power battery, a low-carbon and high efficiency optimization model of cutting parameters is established on the basis of considering the influence of the safety factors on the cutting parameters. Considering the numerical continuity and non-linearity of the model, an improved PSO algorithm is introduced, whose effectiveness is verified by a battery cutting case study. Compared with the cutting parameters determined manually, the optimized cutting parameters have significant effects in reducing carbon footprint and improving cutting efficiency. In addition to cutting parameters, cutting tools or cutting methods would also have an influence on the carbon footprint and consumed time of used power battery cutting process. Therefore, the focus of the further research is to comprehensively consider the relationship between the cutting tools and cutting parameters to make the optimization results more practical with the actual production situation.

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