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Research on Precision Manufacturing Process of Power Battery Electrode Based on Selective Laser Melting

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Abstract

This work proposes an in-depth analysis of the implementation of selective laser melting (SLM) technology in the precision manufacturing of power battery electrodes, which responds to the needs of state-of-the-art energy storage systems for electric vehicles and grid applications. Innovative process control and optimisation strategies led to unparalleled outcomes pertaining to control of microstructure within the electrodes and their electrochemical performance. The research was conducted with an SLM system that has a customised design, incorporating a 200W fibre laser source with a wavelength of 1064nm. It was also paired with an advanced closed-loop control system which relies on thermal imaging on a real-time basis. As part of the experimental framework, a multi-objective optimisation problem was defined and solved using response surface methodology to determine the important relationships between the defining process parameters and the process outputs. Analysis of the data demonstrated electrode performance improvements such as 85% specific capacity retention at 2C rate alongside better electron transfer kinetics due to modification of the pore structure and particle distribution achieved by SLM processing. The system was capable of maintaining stability of material phases during thermal cycles while controlling the pores and surfaces with high accuracy. This investigation presents SLM as a potential means for quality electrode production which can be beneficial for manufacturing batteries on an industrial scale. The results improve energy storage devices with a new accurate and economical method of manufacturing advanced battery electrodes that can be used in electric vehicles and grid storage systems.

Keywords

Selective laser melting; Experimental framework; Electrode; Thermal cycles.

1. INTRODUCTION

The rapid advancement of electric vehicles and energy storage systems has intensified the demand for high-performance lithium-ion batteries, driving innovation in electrode manufacturing processes [1]. Laser-based manufacturing technologies have emerged as promising solutions for precise electrode processing, offering advantages in process control and efficiency [2]. Recent developments in selective laser melting (SLM) technology enable unprecedented control over microstructure and surface properties [3].

Park et al. [4] demonstrated the potential of selective material processing in achieving enhanced energy density and rate capability through optimized electrode architectures. Additionally, Li et al. [5] showed that precise control of laser parameters significantly influences electrochemical properties through regulation of surface morphology and internal structure.

This research investigates the precision manufacturing process of power battery electrodes using selective laser melting technology, focusing on process optimization, quality control, and performance enhancement for mass production applications.

2. SLM THEORY FOR BATTERY ELECTRODE MANUFACTURING

The selective laser melting (SLM) process for battery electrode manufacturing represents a sophisticated approach to precision material processing, where a high-energy laser beam selectively fuses metallic or ceramic powder materials in a layer-by-layer manner. The fundamental mechanism involves complex physical and chemical interactions between the laser beam and electrode materials, characterized by rapid heating, melting, and solidification processes. During the melting phase, the absorbed laser energy induces localized temperature gradients, leading to the formation of a melt pool with specific thermodynamic properties. The heat transfer mechanism in SLM can be described by a three-dimensional transient heat conduction model, incorporating the effects of temperature-dependent material properties and phase changes. The governing equation includes terms for laser energy input, heat conduction, and phase transformation energies. Simultaneously, mass transfer occurs through fluid flow within the melt pool, driven by surface tension gradients (Marangoni effect) and recoil pressure. These phenomena significantly influence the final microstructure and properties of the electrode material.

3. EXPERIMENTAL SYSTEM AND METHODS

The experimental system for selective laser melting of battery electrodes comprises a custom-designed SLM apparatus featuring a fiber laser source with maximum power output of 200W and wavelength of 1064nm. The system incorporates a precision scanning galvanometer system for beam delivery and a sealed build chamber with inert gas atmosphere control. The build platform includes a heating system capable of maintaining temperatures up to 200°C.

Material preparation involves specialized processing of battery electrode materials, including lithium-based compounds and conductive additives, into fine powders with controlled particle size distribution (D50 = 15-45μm). Characterization techniques employ SEM-EDS for morphology and composition analysis, XRD for phase identification, and laser diffraction for particle size analysis.

The process parameter control system implements a closed-loop control strategy based on the fundamental energy density equation:

$$E = \frac{P}{v \cdot h \cdot t} \cdot \eta \tag{1}$$

where E represents energy density (J/mm^3), P is laser power (W), v is scanning speed (mm/s), h is hatch spacing (mm), t is layer thickness (mm), and η is absorption efficiency. The system employs real-time monitoring through:

$$T(x,y,z,t) = T_0 + \frac{AP}{2\pi\lambda} \int_0^t \frac{exp(-\frac{r^2}{4\alpha(t-\tau)})}{4\alpha(t-\tau)} d\tau \tag{2}$$

where T represents temperature distribution, α is thermal diffusivity, and r is radial distance.

Testing methods include in-situ thermal imaging, post-process mechanical testing, and electrochemical characterization through cyclic voltammetry and impedance spectroscopy.

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Analysis protocols follow standardized procedures for battery electrode evaluation, with data acquisition at 1kHz sampling rate.

4. PROCESS PARAMETERS OPTIMIZATION AND CONTROL

Process parameter optimization in SLM for battery electrode manufacturing requires systematic identification and control of critical parameters that influence the final product quality. The key process parameters include laser power (P), scanning speed (v), hatch spacing (h), and layer thickness (t), which collectively determine the energy density distribution. Parameter optimization employs Design of Experiments (DOE) methodology using response surface methodology (RSM) to establish relationships between process parameters and output characteristics.

The process window establishment utilizes a multi-objective optimization approach, considering both quality metrics and manufacturing efficiency. The operational limits are defined by:

$$P_{min} \le P \le P_{max} \quad v_{min} \le v \le v_{max} \quad h_{min} \le h \le h_{max}$$

Real-time monitoring and control strategies implement a hierarchical control architecture, as shown in Figure 1.

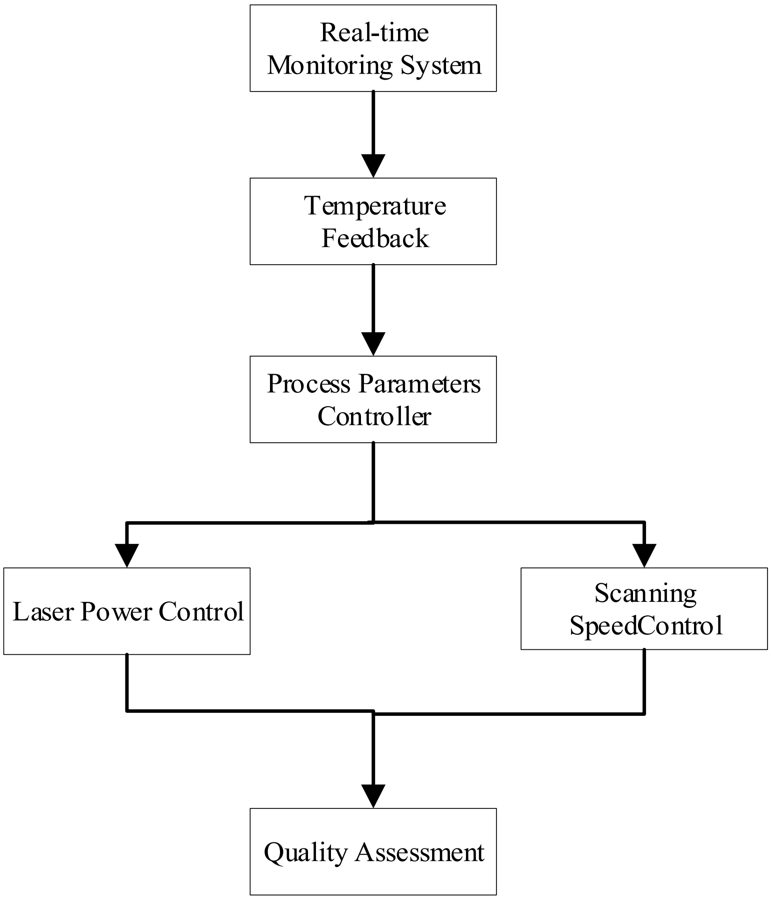

Figure 1. Hierarchical Control Architecture for SLM Process Parameter Optimization

The control system employs feedback loops for temperature regulation and quality assessment, enabling dynamic adjustment of process parameters to maintain optimal manufacturing conditions. This adaptive control strategy ensures consistent product quality while accommodating material property variations and environmental fluctuations.

5. ELECTRODE MATERIAL MICROSTRUCTURE AND PROPERTIES ANALYSIS

The microstructural and properties analysis of SLM-processed battery electrodes reveals distinctive characteristics across multiple scales. Electron microscopy observations indicate a hierarchical pore structure with controlled porosity distribution, essential for electrolyte penetration and ion transport. X-ray diffraction patterns confirm the preservation of active material crystal structure post-processing, with phase stability maintained throughout the thermal cycles.

Surface morphology analysis using high-resolution SEM imaging demonstrates uniform particle distribution and interconnected network formation, as illustrated in Figure 2.

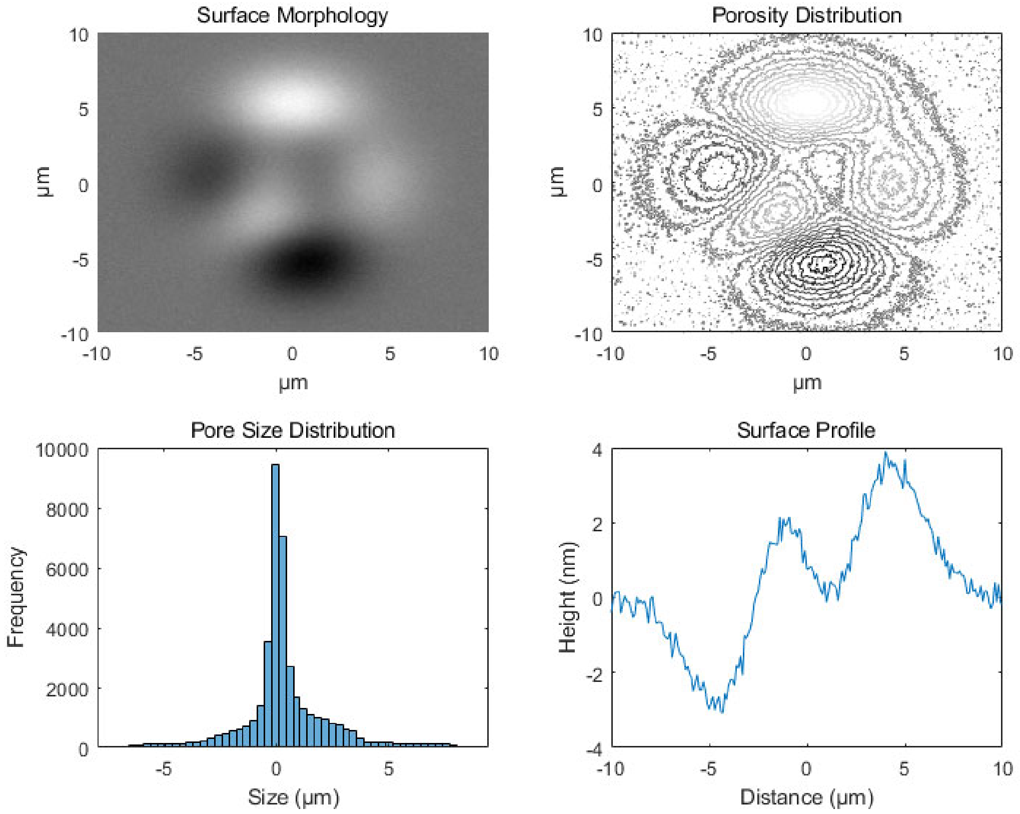

Figure 2. Microstructural Analysis of SLM-Processed Battery Electrode Surface

Electrochemical performance evaluation reveals enhanced rate capability compared to conventional electrodes, with specific capacity retention of 85% at 2C rate. Cyclic voltammetry measurements show well-defined redox peaks, indicating efficient electron transfer kinetics. Impedance spectroscopy analysis confirms reduced charge transfer resistance, attributed to the optimized microstructure achieved through SLM processing.

6. CONCLUSIONS

This research successfully developed a selective laser melting process for battery electrode manufacturing, achieving controlled microstructure and enhanced electrochemical properties. The established parameters and monitoring system enable stable production of high-quality electrodes. SLM technology shows promise for next-generation battery manufacturing, with future focus needed on process scaling and stability evaluation.

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