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Structural Performance Analysis of Load-Bearing Aluminum Alloy Liquid Cold Plates

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Abstract: As a core heat exchange component in battery thermal management systems, the liquid cold plate must not only perform heat dissipation functions but also withstand multiple loads including battery module weight and internal coolant pressure. Its structural load-bearing performance directly affects the sealing, reliability, and service life of the system. This paper focuses on the structural load-bearing performance of aluminum alloy liquid cold plates and systematically reviews the structural forms and load-bearing characteristics of liquid cold plates. The review emphasizes two aspects: deformation and stress response under hydrostatic pressure, and stiffness and strength evaluation under heavy-load conditions. The analysis indicates that the load-bearing performance of liquid cold plates is mainly influenced by material properties, cross-sectional geometric characteristics, and internal support structure layout. The flow channel ribs not only guide the coolant but also serve a structural reinforcement function, significantly improving plate stiffness. Stress concentration zones are typically located at geometric discontinuities, which are the main causes of structural failure. This paper also summarizes the main analysis methods for structural performance of liquid cold plates and proposes future research directions, aiming to provide a reference for the structural-functional integrated design of liquid cold plates.

Keywords: liquid cold plate; structural performance; load-bearing analysis; aluminum alloy; strength evaluation

1.INTRODUCTION

With the rapid development of the new energy vehicle industry, the performance requirements for liquid cold plates in lithium-ion battery thermal management systems have become increasingly stringent. As the core heat exchange component of battery thermal management, the liquid cold plate长期承受internal pressure loads from the coolant, and its structural strength is directly related to the sealing and operational reliability of the system. Excessive plastic deformation of the liquid cold plate under working pressure may lead to flow channel blockage, weld cracking, or even coolant leakage, which could trigger serious safety accidents such as battery thermal runaway. Therefore, research on the structural load-bearing performance of liquid cold plates is of significant engineering importance for ensuring product structural safety.

Currently, liquid cold plates are mostly manufactured using aluminum alloy stamping and brazing processes, consisting of a flat plate and a flow channel plate composite structure. The flat plate is a thin-walled cover plate structure, while the flow channel plate contains complex fluid channels and supporting ribs inside. The stiffness characteristics of these two components differ significantly. Existing research mainly focuses on the heat transfer performance optimization of liquid cold plates, with relatively insufficient systematic analysis of structural strength. Some scholars have compared the deformation characteristics of various flow channel schemes through load-bearing tests, confirming that the flow channel structure significantly enhances the overall stiffness of the liquid cold plate. However, these studies focused on static load-bearing conditions and did not深入involve coupled analysis of internal fluid pressure loads and overall assembly load-bearing. Although some energy storage battery pack liquid cooling structural designs mention strength verification, they do not深入analyze the stress distribution patterns of different components.

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In engineering practice, the working pressure of liquid cold plates is typically on the order of 0.2 MPa, while they must also bear battery module weights ranging from hundreds of kilograms to over one ton. Sufficient strength margins must be reserved for pressure fluctuations and impact conditions. Due to the significant geometric differences between the flat plate and the flow channel plate, their deformation responses and stress concentration characteristics under identical loads are fundamentally different. Clarifying these differential patterns is a prerequisite for structural optimization design. In view of this, this paper systematically reviews the research status and analysis methods of the structural load-bearing performance of aluminum alloy liquid cold plates from two dimensions: hydrostatic pressure loads and heavy-load conditions. It reveals the reinforcement mechanism of flow channel ribs on structural stiffness and identifies stress concentration risk areas, providing a theoretical basis for structural strength improvement of liquid cold plates.

2 STRUCTURAL FORMS AND LOAD-BEARING CHARACTERISTICS OF LIQUID COLD PLATES

2.1 Typical Structural Forms

Liquid cold plates are typically composed of an upper cover plate (flat plate) and a lower plate (flow channel plate) joined through brazing. The flat plate is a homogeneous thin-walled cover plate with a smooth surface and no protruding structures, primarily serving as a sealing and heat transfer interface. The flow channel plate internally forms continuous fluid channels through stamping, with metal ribs separating adjacent channels. The channel layout typically follows a serpentine or parallel distribution, with ribs intersecting in a grid pattern. After brazing, these ribs form a closed support structure with the flat plate, effectively arranging distributed stiffeners on the back side of the flat plate.

2.2 Load-Bearing Load Types

Liquid cold plates primarily withstand two types of loads during operation: first, internal coolant pressure loads, typically on the order of 0.2 MPa, which act on the inner walls of the flow channels and cause an outward bulging deformation tendency in the thin plates; second, the gravitational load of the battery modules above, which is transmitted to the liquid cold plate surface through the cell bottoms via thermal pads as an out-of-plane uniform pressure. In large-capacity energy storage systems, this load has increased from hundreds of kilograms in early designs to over one ton, imposing higher requirements on the stiffness and strength of the liquid cold plate and its supporting structure.

2.3 Performance Evaluation Indicators

The main evaluation indicators for the structural load-bearing performance of liquid cold plates include: maximum deformation——an intuitive indicator reflecting the overall stiffness of the structure; excessive deformation will affect the contact gap between cells and the liquid cold plate, increasing thermal contact resistance; maximum equivalent stress——reflecting the structural strength reserve; when stress exceeds the material yield strength, plastic deformation occurs, potentially leading to irreversible structural damage; stress concentration factor——reflecting the degree of stress amplification at geometric discontinuities, which is an important parameter for evaluating fatigue life.

3 CURRENT RESEARCH STATUS OF LIQUID COLD PLATE STRUCTURAL PERFORMANCE

3.1 Structural Response under Hydrostatic Pressure

The hydrostatic deformation of liquid cold plates is a typical small-deflection bending problem of thin plates. Under internal fluid pressure, the flat plate exhibits a membrane bulging deformation pattern, with deformation increasing from the edges toward the center, and the maximum deformation occurring in the central region of the plate surface. Thin plate theory analysis shows that deformation is linearly related to the pressure load (within the elastic range), inversely proportional to the cube of the plate thickness, and proportional to the fourth power of the plate span.

In terms of stress distribution, maximum stress typically occurs at geometric discontinuities, such as flow channel corners, fillet transition zones, and rib intersections. These regions experience sharp deviations in stress flow lines due to cross-sectional abrupt changes, resulting in significant stress concentration. When local stress exceeds the material yield strength, plastic yielding occurs. Although the overall structure may remain stable, the accumulation of local plastic strain can become a hidden risk for fatigue crack initiation.

3.2 Load-Bearing Performance under Heavy-Load Conditions

Under the gravitational load of battery modules, the liquid cold plate and the bottom support frame form a combined load-bearing system. The overall structural bending stiffness is mainly determined by the bottom support beams, while the liquid cold plate panel primarily承担load transmission and distribution, with limited direct contribution to the overall stiffness. Under such conditions, deformation peaks typically occur at the mid-span positions of the support beam frames, i.e., the large-span intervals without lateral supports.

The stress distribution under heavy-load conditions exhibits two levels: first, overall bending stress, which is uniformly distributed and relatively low in magnitude; second, local stress concentration, mainly concentrated at the corner transitions between support beams and frames, weld zones, and cross-sectional abrupt change positions, where the peak stress can be several times the average stress level. Such stress concentrations are the main risk sources of structural failure.

3.3 Key Influencing Factors

The key factors affecting the structural load-bearing performance of liquid cold plates can be summarized into three aspects: in terms of material properties, the yield strength and Young's modulus of aluminum alloy determine the threshold for plastic deformation and the magnitude of elastic deformation; in terms of cross-sectional geometric characteristics, plate thickness, flow channel depth, and rib width directly affect the section moment of inertia, which is the decisive factor for stiffness; in terms of support layout, the spacing and distribution pattern of internal ribs determine the support span of the panel. Dense ribs can effectively reduce the effective span of the panel and decrease deflection deformation.

4 STRUCTURAL PERFORMANCE ANALYSIS METHODS

4.1 Analytical Methods

Based on the small-deflection bending theory of thin plates, analytical solutions for the deformation and stress of regularly shaped liquid cold plates under uniform loads can be obtained. Classical plate and shell theories provide a series of closed-form solutions, suitable for rapid estimation and parameter trend analysis during the preliminary design stage. However, analytical methods have difficulty handling complex flow channel geometries and nonlinear material behavior, limiting their application range.

4.2 Finite Element Numerical Methods

The finite element method has become the mainstream tool for structural performance analysis of liquid cold plates. By extracting the mid-surface and establishing shell element models, the computational scale can be significantly reduced while ensuring calculation accuracy, making it suitable for strength analysis of thin-walled structures. For analysis of complete assemblies under heavy-load conditions, a combined model including the liquid cold plate, support beams, and profile frame should be established to account for load transmission and cooperative deformation among components.

In terms of mesh generation, local refinement should be applied in stress concentration regions to ensure accurate capture of stress gradients. Boundary conditions should simulate actual assembly constraints, and load application methods should be selected as uniform pressure or equivalent concentrated forces based on the characteristics of the working conditions. Interpretation of calculation results should distinguish between overall bending stress and local stress concentration to identify the true risk sources of failure.

4.3 Experimental Validation

Actual load-bearing tests and pressure tests are important means of validating the reliability of analysis results. Pressure tests can obtain the deformation-pressure curves of liquid cold plates for comparison and calibration with simulation results. Load-bearing tests can evaluate the actual deformation of liquid cold plates under module weight. Experimental data can provide a basis for calibration of simulation models,弥补the uncertainties in material constitutive parameters and boundary condition simplifications in numerical methods.

5 STRUCTURAL OPTIMIZATION DIRECTIONS AND PROSPECTS

5.1 Structural Optimization Directions

The optimization of structural load-bearing performance of liquid cold plates should focus on the following directions: in terms of stress concentration mitigation, increasing fillet radius, optimizing geometric transition forms, and adding unloading grooves at corners can effectively reduce peak stress; in terms of stiffness enhancement, increasing the section moment of inertia of the bottom profile (e.g., optimizing to a "日" or "田" shaped cross-section), adding auxiliary supports at mid-span to reduce support span, and optimizing internal rib layout can significantly improve overall stiffness; in terms of material matching, the liquid cold plate body should use aluminum alloy with excellent thermal conductivity, while the support frame should use high-strength steel to achieve collaborative design of heat dissipation and load-bearing functions.

5.2 Future Research Prospects

Future research can深入地explore the following aspects: conducting fatigue life analysis to evaluate the long-term service reliability of structures under cyclic loads; performing brazed weld strength verification to identify weak links in weld zones; exploring lightweight design approaches to reduce structural weight while meeting strength and stiffness requirements; and combining thermal-mechanical coupling analysis to evaluate the influence of temperature fields on structural load-bearing performance, achieving collaborative optimization of thermal management and structural strength.

6. ACKNOWLEDGMENTS

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