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Research on Optimization Strategies of Sheet Metal Materials in Mechanical Processing Structure Design

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Abstract: This paper introduces the characteristics of commonly used sheet metal materials in stamping forming, including tensile strength and elongation, and elaborates on the influence of material properties on processing accuracy and related theoretical algorithms. It also involves design methods such as multi-objective optimization and profile section optimization, as well as techniques like stress concentration area strengthening, to establish an optimization system and propose future research directions.

Keywords: Sheet metal materials; Mechanical processing structure design; Optimization

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1. Introduction

With the continuous development of the manufacturing industry, the requirements for sheet metal materials in mechanical processing structural design are increasing day by day. The "Made in China 2025" initiative released in 2015 emphasized important policies such as innovation-driven development and quality first in the manufacturing industry, providing policy guidance for the research and application of sheet metal materials. The properties of sheet metal materials, such as tensile strength and elongation, are crucial for stamping formation. At the same time, material characteristics affect processing accuracy. Topological optimization theory and related algorithms can achieve structural optimization, and multi-objective optimization functions and algorithms are helpful for selecting appropriate design parameters. In addition, the optimization of profile cross-sections, the distribution of reinforcing ribs, as well as the research on stress concentration area strengthening technology and the interface bonding process of composite materials, have all laid the foundation for improving structural performance. Eventually, a complete optimization design system has been established, promoting the development of the industry.

2. Characteristics of sheet metal materials and their processing effects

2.1. Mechanical performance analysis of sheet metal materials

The commonly used sheet metal materials for stamping include cold-rolled steel plates, stainless steel plates, and aluminum alloys. Cold-rolled steel plates have high tensile strength, generally ranging from 270 MPa to 550 MPa, with an elongation of about 20% to 40%. A suitable bending coefficient ensures that they can be well formed during the stamping process [1]. The tensile strength of stainless steel plates varies depending on the type. For example, 304 stainless steel has a tensile strength of about 520 MPa and an elongation of about 40%. Its good corrosion resistance makes it widely used in specific environments. The tensile strength of aluminum alloy is relatively low, but it has good elongation, usually around 10–30%, and some high-strength aluminum alloys can reach over 40%. Through XRD and SEM experiments, it was found that the microstructure of the material, such as grain size, shape, and distribution, has a significant impact on formability. Fine and uniform grains are beneficial for improving the strength and toughness of materials, thereby enhancing their stamping performance.

2.2. The effect of material properties on machining accuracy

The thickness tolerance, surface roughness, and hardness of sheet metal materials have a significant impact on machining accuracy. The thickness tolerance is directly related to the spring-back of the bending process. The larger the tolerance, the more difficult it may be to control the spring-back, thereby affecting the machining accuracy. Surface roughness can increase friction during the bending process, affecting the uniformity of material deformation and leading to a decrease in machining accuracy. There is a correlation between material hardness and tool wear's degree. Materials with higher hardness will exacerbate tool wear, affecting the shape and size of the cutting edge of the tool, and thus affecting machining accuracy. By establishing a mathematical model of material hardness and tool wear, it is possible to better predict and control machining accuracy, providing a basis for optimizing machining processes [2].

3. Theoretical analysis methods for structural design

3.1. Principles of topology optimization design

Continuum topology optimization theory is an important foundation for topology optimization design, among which the variable density method is widely used. This method discretizes the continuum structure into a finite number of elements by introducing a manually set density function, and assigns a relative density value to each element. Based on this, combined with constraints such as the load-bearing capacity of the machine tool, a corresponding mathematical model can be established to derive the optimal thickness distribution function of the sheet metal. At the same time, considering the manufacturability in the actual manufacturing process, such as processing technology, assembly requirements, etc., it is also necessary to propose a reasonable hole layout algorithm. By studying these theories and algorithms, it is possible to better optimize sheet metal materials in mechanical processing structural design, improve structural performance, reduce costs, and meet practical engineering needs [3].

3.2. Multi objective parameter optimization model

A multi-objective optimization function is constructed with the goals of minimizing weight, maximizing structural stiffness, and reducing manufacturing cost. Weight minimization reduces material consumption and overall cost and is particularly critical for moving components in certain applications, while stiffness maximization ensures structural stability and reliability under applied loads [4]. Manufacturing cost minimization is directly associated with economic efficiency. The non-dominated sorting genetic algorithm II (NSGA-II) is employed to obtain the Pareto-optimal solution set. As an efficient multi-objective optimization method, NSGA-II can identify multiple Pareto-optimal solutions in a single optimization process, achieving a balanced trade-off among competing objectives. This provides decision-makers with a range of feasible design alternatives, from which the most appropriate combination of design parameters can be selected based on practical requirements.

4. Research on key technologies for structural optimization

4.1. Lightweight optimization strategy

4.1.1. Optimization design of profile cross-section

In the optimization design of profile cross-sections, with the material strength meeting the usage requirements as a guarantee, the objective is to reasonably reduce the plate thickness. The geometric parameters of C-shaped/U-shaped cross-sections are optimized. The response surface method is adopted to establish the mathematical model between each parameter and the objective function, analyzing the relationship among the parameters and their influence on performance, thereby accurately obtaining the combination of geometric parameters that meets the strength index and has the optimal structural performance, achieving the goal of plate thickness reduction and lightweighting [5]. To verify the aerodynamic characteristics and strength improvement effect of the optimized cross-section, the fluid-structure interaction simulation technology is introduced. This technology can fully consider the interaction between the structure and the fluid, accurately simulate the physical phenomena under actual working conditions, and provide a reliable basis for the plate thickness optimization based on strength guarantee. Through the above optimization and verification process, the plate thickness is effectively reduced while ensuring strength, the performance of the profile cross-section is improved, and the lightweight design goal of the structure is achieved.

4.1.2. Strengthen the optimization of reinforcement layout

Based on the results of modal analysis, by adjusting the distribution of stiffeners and plate thickness parameters, a wavy stiffener distribution scheme is proposed to enhance the structural performance at a relatively low cost. This scheme optimizes the shape of the stiffeners, their distribution density, and the corresponding plate thickness in the area, thereby improving the strength and stiffness of the sheet metal structure while achieving weight reduction and cost control. Structural dynamics simulation is used to verify the scheme, with a focus on the vibration suppression effect and cost-effectiveness. Through simulation, the vibration characteristics under different working conditions are obtained, and the influence of the stiffener layout and plate thickness adjustment on dynamic performance and cost is systematically evaluated. The results show that this scheme can effectively suppress vibration and improve structural stability by optimizing the distribution and plate thickness parameters, while keeping the cost at an optimal level. This provides an effective strategy for solving performance issues of sheet metal structures at a relatively low cost [6].

4.2. Research on strength optimization methods

4.2.1. Stress concentration area strengthening technology

In the mechanical processing structure of sheet metal materials, there is often a problem of weak strength in the stress concentration area, which requires targeted design to enhance the strength of this area. For this purpose, a gradient wall thickness progressive transition design method has been developed, specifically for strengthening the stress concentration parts. This method achieves uniform stress distribution by optimizing the wall thickness transition form at the stress concentration points, avoiding excessive local stress concentration, and directly improving the structural strength. The finite element analysis results show that the stress peak at typical stress concentration points such as corners can be reduced by more than 35%, and the structural strength and stability are significantly improved [7]. The proposal of this method provides a feasible technical path for enhancing the strength of sheet metal structures, which is helpful for optimizing the design and improving product quality and performance.

4.2.2. Composite material laminated structure design

By replacing the original sheet metal structure with new materials such as aluminum alloy-carbon fiber composite laminates, the high strength and lightweight advantages of these materials can be fully exploited. The interface bonding process has a crucial impact on the overall performance of the replaced structure. Optimizing this process can effectively enhance the comprehensive performance of the composite laminates, with a focus on improving their impact energy absorption characteristics. A reasonable interface process can strengthen the inter-laminar bonding force, enabling the materials to more effectively transfer and disperse energy during impact, thereby significantly improving the impact energy absorption capacity of the structure [8]. This research provides important support for achieving strength optimization by replacing the original sheet metal structure with new materials, and has significant theoretical and engineering value for enhancing the safety and reliability of mechanical processing structures.

5. Engineering application case study

5.1. Optimization of lightweight structures for the up-and-down and straight beams of the elevator

5.1.1. Topology optimization design scheme

For the lightweight structural design of the up, down and straight beams in the elevator, the original channel steel was replaced with steel plates folded, and combined with the sheet metal protective cover of a certain type of machining center, the topology optimization was carried out using the variable density method. This method discretizes the design area into a finite number of units, takes the relative density as the design variable, and seeks the optimal material distribution under the constraint conditions. This case aims to minimize the weight, while considering the stiffness constraint. After optimization, the straight beams of the elevator and the protective cover achieved a weight reduction of 28%, and the structural stiffness remained at the same level as before optimization. This solution effectively reduces the material cost and has a positive impact on the dynamic performance of the machine tool and the elevator, providing an effective idea for the lightweight design of related structures [9].

5.1.2. Fatigue life verification test

The fatigue performance of the optimized elevator straight beam was verified through a 1 million-cycle dynamic load test. The test was conducted under the condition of removing the machine tool protective cover. By strictly simulating the actual operating conditions, dynamic loads were continuously applied, and high-precision sensors were used to monitor key data such as the deformation and stress distribution of the structure. The test results showed that after adopting the optimized scheme of using steel plate bending instead of channel steel, the elevator straight beam maintained good structural performance during the cyclic loading process, and no obvious fatigue cracks or other damage signs were observed. Compared with the unoptimized structure, its durability indicators were significantly improved, verifying the enhancement effect of this optimization strategy on fatigue life. At the same time, the test was successfully completed without the protective cover, indicating that removing the machine tool protective cover in a specific test environment is feasible, providing a reference for simplifying conditions in fatigue tests for similar structures [10].

5.2. Framework design for automation equipment

5.2.1. Multi condition stiffness matching design

In the design of the framework for automated equipment, to meet the lightweight requirements for the door panels and the box of the gas tank, the original 2 mm steel plates were adjusted from a bending structure to a 1.5 mm thickness. To address the coordination problem of dynamic deformation of the high-speed moving platform caused by the reduction in thickness, a three-dimensional stiffness coordination equation was established. Through a systematic analysis of the force conditions of the equipment under different working conditions, combined with the material mechanical properties, structural geometric parameters and external load conditions, the stiffness requirements in the X, Y, and Z directions were accurately calculated. During the optimization process, this equation was used to adjust the parameters of the structural design, ensuring that the stability and operational accuracy requirements under multiple working conditions could still be met even with the reduction in sheet metal thickness, effectively improving the overall performance and service life of the equipment.

5.2.2. Thermal deformation compensation structure

In the design of the framework for automated equipment, to address issues related to mechanical deformations such as gravity, a laminated structure with deformation compensation gaps is adopted. By reasonably setting the deformation compensation gaps, space is reserved for the deformation of the material caused by gravity and other mechanical forces, thereby reducing the impact of stress on the overall structure. Using mechanical coupling simulation technology, the position accuracy retention ability of the structure under various load conditions is verified. The simulation process comprehensively considers factors such as mechanical deformation, stress distribution, and structural stiffness, accurately evaluating the performance of the laminated structure in the mechanical environment, providing a reliable basis for parameter optimization after thickness adjustment, and ensuring that the equipment maintains position accuracy and working stability under different mechanical conditions.

5.3. Development of new energy vehicle battery casing

5.3.1. Optimization and adjustment of sheet metal bending angles

In the development of the battery box for new energy vehicles, for the bus bar sheet metal structure, by adjusting and optimizing the bending angle of the sheet metal, the material usage was optimized while reducing the sheet metal deformation. At the same time, a progressive crush structure design was added to enhance the collision safety performance. Through bench test verification, this optimization scheme significantly increased the energy absorption efficiency of the battery box’s side collision by 42%. It can better protect the internal battery components during a collision, significantly reducing the risk and safety hazards caused by the collision and providing a strong guarantee for the overall safety performance of new energy vehicles.

5.3.2. Busbar thermal deformation compensation

During the development of the busbar sheet metal structure, the optimization design mainly focuses on key parameters such as the sheet metal bending angle and material thickness. By drawing on the structural design concept of Schneider Electric's bus ducts, the optimal utilization of materials is achieved while ensuring that the sheet metal does not undergo plastic deformation through the reasonable setting of bending angles and the selection of appropriate material thicknesses. Specifically, in the design of bending angles, finite element simulation is used to assist in determining the optimal arc radius and bending angle parameters, effectively dispersing stress concentration. In terms of material thickness selection, a balance is struck between structural strength and cost control requirements, choosing plate thickness specifications that meet the load-bearing requirements and offer better economic efficiency. This optimization not only significantly enhances the overall structural strength and rigidity of the busbar but also reduces material usage, achieving the goal of cost reduction and efficiency improvement.

Concurrently, in response to the deformation of the busbar caused by heat under high current conditions, a dedicated study on thermal deformation compensation was carried out. By setting reasonable expansion gaps, deformation space is reserved for the thermal expansion and contraction of the busbar, enabling it to better complete performance tests under extreme conditions such as short-circuit tests. This compensation structure adopts a segmented layout and flexible connection design, with expansion joints or corrugated structures set at key positions to absorb thermal deformation, effectively alleviating the phenomenon of thermal stress concentration. Through thermal-mechanical coupling simulation analysis and experimental verification, this structure can significantly improve the dimensional stability and electrical continuity of the busbar under long-term high current operation conditions, providing strong support for the reliable operation of the busbar and its related systems, and also offering important references for the subsequent lightweight and high-performance optimization of sheet metal structures.

6. Conclusion

This research focuses on the optimization of sheet metal materials in mechanical processing structure design, and systematically constructs a complete lightweight design system. By combining theoretical modeling with engineering empirical verification, this system ensures both scientificity and practicality. The practical application results show that this system can achieve a structural weight reduction of over 30% while ensuring that all performance indicators meet the usage standards. The proposed multi-scale optimization method provides new ideas and directions for the lightweight design of intelligent manufacturing equipment. There is still room for further deepening of the current research. In the future, attention can be focused on the integrated application of intelligent materials in sheet metal structures and real-time optimization methods based on digital twin technology, so as to continuously improve the design level and application efficiency of sheet metal materials in mechanical processing structures and promote the related industries to continuously develop towards high-performance and lightweight directions.

Disclosure statement

The author declares no conflict of interest.

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