論文の内容の要旨

論文題目　Novel Design and Fabrication of Metal Face/3D CFRP Composite Hybrid Structure

（メタルフェースと 3D CFRP コアからなる複合材料の新たな構造設計と評価）

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The design and fabrication of lightweight hybrid structures with optimal mechanical performance, production efficiency and improved functionality has always been driven by the pursuit of further reduction of energy consumption and greenhouse gas emissions. However, the technical issues associated with the design and production processes, such as the low manufacturing efficiency and high production cost, the limited formability and restricted mechanical performance and functionality, severely hindered the widespread use of such lightweight multifunctional hybrid structures. This doctoral thesis aims to overcome these engineering challenges by proposing a new type of metal face/3D CFRP core hybrid structure with enhanced mechanical performance productivity and formability achieved by more effective design strategies and efficient production processes.

Two main strategies were proposed for the design and fabrication of lightweight formable metal face/3D CFRP core hybrid structures, in which the shape design and conventional production processes were firstly proposed in the first strategy while the second strategy relies on topology optimization and additive manufacturing. To be specific, the suitable inner core structure with superior mechanical property was designed and efficiently produced by warm stamping of CFRTP sheet. The effects of material properties of face sheets and core, sandwich geometries, forming tool geometries, core shapes, forming processes and forming temperatures on formability of sandwich sheets were systematically investigated by experiments and theoretical analyses. The homogenization-based topology optimization (HMTO) method was firstly integrated with the tetrahedral truss-based lattice structure to optimize the stiffness and later the elastically isotropic plate-based lattices with superior structural efficiency was further proposed to integrate with HMTO to improve the design efficiency, manufacturability, structural isotropy and computational efficiency. The stiffness and formability of sandwich sheets were simultaneously optimized by integrating the density-based topology optimization method with the multi-stage genetic algorithm. The feasibility of effective design and efficient fabrication of hybrid metal face/CFRP core composite sheets with superior mechanical property, formability as well as productivity is demonstrated by a series of investigations presented in this thesis.

1st part: Shape design and conventional fabrication of formable sandwich sheet

Comprehensively considering the mechanical property, manufacturability and failure resistance ability, a truncated dome core made of carbon fiber reinforced thermoplastics (CFRTP) was determined to be the inner macrostructure of sandwich sheets. The proposed truncated dome core structure was composed of a periodic array of domes which were introduced into an initially flat CFRTP sheet through warm stamping. The numerical investigation shows that the optimal relative density of the truncated dome core is 0.22 in terms of comprehensive consideration of bending stiffness, shear modulus and face buckling degree. The optimal forming conditions of CFRTP sheet were investigated prior to the continuous fabrication process of long CFRTP core by piecewise sectional forming technology. The flexural properties were tested by three-point bending, and formability of sandwich sheets was evaluated experimentally by cold and warm L-bending and draw-bending tests. The results indicate that the sandwich sheets composed of metallic face sheets and CFRTP core have better formability when cold formed, while the sandwich sheets composed of CFRTP face sheets and CFRTP cores have superior formability when warm formed. The development of formable metal face/CFRP core sandwich sheets is expected to expand the application range of sandwich structures and promote the use of lightweight parts in engineering fields.

In the subsequent study, firstly, for the sandwich sheets with a truncated dome core designed in the previous chapter, theoretical analyses were conducted to determine the conditions required for successfully forming these sandwich sheets into curved shapes. Experimental results of formability tests agree well with the theoretical predictions, which demonstrates the validity of the theoretical models. Sandwich sheets with both A2017P and SUS304 face sheets of a thickness of 0.5 mm can be bent without any failure at a bending radius of 60 mm. To further improve structural performance, bendability and potential functionality of metal-based sandwich sheets, the 3D lattice cores were sandwiched between thin metallic face sheets. The bending properties of sandwich sheets with 3D printed CFRP lattice cores originating from basic topologies of spherical shell, tetrahedral truss and tetrahedral plate were systematically investigated. The effects of core topologies, core relative densities, core heights, face sheet thicknesses on structural properties were clarified. The common failure modes during bending of sandwich sheets, such as face buckling and shear failure of core, were deeply investigated by theoretical models and experimental tests. At a prescribed radius of 60 mm, the sandwich sheets with the bilayered dome, octet truss and plate lattice cores of relative density of 50%, height of 6 mm and face sheet thickness of 0.5 mm are bendable. The feasibility of design and production of bendable sandwich sheets with 3D lattice cores is demonstrated based on the theoretical and experimental validations. The designed bendable sandwich sheets can be adopted to replace conventional heavy monolithic metal sheets in various engineering applications, which is anticipated to fulfill the high demand for lightweight functional materials.

2nd part: Design and fabrication of inner macrostructure with enhanced stiffness and formability via topology optimization and additive manufacturing

A new microlattice dome structure has been proposed, in which the solid part of the conventional dome structure is replaced by less dense and less brittle stretch-dominated tetrahedral microlattices. By integrating homogenization-based topology optimization with a tetrahedral microlattice, the optimal distribution of the microlattice was determined under compression and three-point bending loads to maximize the stiffness and energy absorption of the microlattice dome. The specific compressive stiffnesses of the optimized variable-density models with large and small cell sizes were improved by 33.8% and 91.8%, respectively, compared with the unoptimized uniform-density models. Compared with the unoptimized uniform-density models, the bending stiffnesses of the optimized variable-density models with large and small cells are increased by 81.6% and 76.9%, respectively. For the compression models, the energy absorption of the optimized variable-density structures with the large and small cells was improved by 72.2% and 124.2%, respectively. The energy absorption of the optimized variable-density models with the large and small cells is increased by 61.8% and 33.3%, respectively, during the three-point bending process. The compressive and bending stiffnesses of the optimized variable-density microlattice domes are proved to be 41.8% and 33.7% higher than those of the conventional solid domes, while the energy absorption of the microlattice dome during compression and three-point bending is increased by 297.5% and 85%, respectively. Investigation of the cell size effect on the mechanical properties of the microlattice dome reveals that a larger cell size contributes more to the weight-specific stiffness and energy absorption capability at a given overall volume fraction constraint. The above significant findings prove that a microlattice dome with high weight-specific stiffness and energy absorption can be designed by integrating topology optimization and lattice structures. The homogenization-based topology optimization and construction methods described in this paper are universal and can be used to optimize and design structures with arbitrary macro shapes with microlattices as constituent units, which is of great significance for the development of ultralight and ultrastiff structures.

Elastically isotropic plate–lattices with superior mechanical properties were firstly proposed to be integrated with the HMTO method to improve design manufacturability, structural efficiency, structural isotropy and computational efficiency. The mechanical properties and elastic isotropy of representative truss–lattices and plate–lattices were investigated, after which the SC–FCC plate–lattice with excellent structural efficiency and elastic isotropy was integrated with the HMTO method to optimize two typical examples. The results indicate the proposed method can significantly improve structural efficiency including stiffness and energy absorption capability. Together with more advantages that this approach is easily implementable and generates designs suitable for AM, the proposed method can be expected to promote the development of ultralight and ultrastiff structures.

A new topology optimization method, in which the density-based topology optimization was integrated with multi-stage GA, was proposed for the design of sandwich sheets with optimal bending stiffness while maintaining good formability. The theoretical core shear failure and face buckling constraints were deduced and incorporated in two topology optimization schemes to design the inner core topology for formable sandwich sheets, in one of which the formability of the sandwich sheets was optimized and in the other one the bending stiffness was optimized while fulfilling potential failure constraints. Three-point bending tests indicate that the bending stiffness and energy absorption capability of sandwich topologies obtained by the proposed optimization scheme can be effectively improved. Comparing the structures obtained by two optimization schemes, the bending stiffness of sandwich topologies with the core density of 50% and 62.5% are improved by 41.58% and 41.49%, while the energy absorption capabilities are improved by 13.60% and 29.40% respectively. L-bending tests show that potential failures including core shear failure, core–face sheet delamination and face buckling of most optimized sandwich topologies can be well suppressed. Draw-bending tests indicate that the formability of optimized sandwich topologies can be effectively improved, and corresponding failure modes are consistent with the sandwich topological characteristics. The validity of the design strategy is demonstrated, that is, through the proposed topology optimization approach, the sandwich sheets with good formability and improved bending stiffness can be designed, which is expected to expand the applications of sandwich sheets with better formability and superior mechanical properties.

To sum up, the feasibility of effective design and efficient fabrication of hybrid metal face/CFRP core composite sheets with superior mechanical property, formability as well as productivity is demonstrated by a series of investigations presented in this thesis. The designed and produced sandwich sheets have superior mechanical property, better formability and potential multifunctionality. They can used to replace the conventional heavy sheet metals widely used in aerospace, automotive and other industries for weight saving and improvement of structural efficiency, which is imperative for the reduction of greenhouse gas emissions and energy consumption.