

Construction and Mechanism Analysis of Digital Collaborative Design Theoretical System for Additive-Subtractive Integrated Manufacturing

Yueqin Liu*

Inner Mongolia Technical College of Mechanics & Electrics, Hohhot 010070, Inner Mongolia, China

**Author to whom correspondence should be addressed.*

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Abstract: Additive-subtractive integrated manufacturing combines the advantages of additive manufacturing and subtractive manufacturing. Featuring rapid free-form forming and high-precision machining, it represents an important development direction for manufacturing technologies of complex special-shaped components. Conventional additive and subtractive machining operate independently, suffering from data disconnection and process segmentation. How to give play to the strengths of digital collaborative design, open up the full-process data links covering design, simulation, process planning, additive forming and finish machining, and improve the technological level of additive-subtractive hybrid manufacturing has become a critical issue for the development and application of additive-subtractive integrated-manufacturing technology. This paper expounds the connotations of additive-subtractive integrated manufacturing and digital collaborative design, puts forward the theoretical system of digital collaborative design for additive-subtractive integrated manufacturing, and analyzes the internal mechanism of digital collaborative design in additive-subtractive integrated manufacturing. Taking lightweight special-shaped automotive components as the application carrier for case study, it aims to clarify the action path of digital collaboration in additive-subtractive hybrid forming, and provide theoretical references and practical ideas for the process development of additive-subtractive integrated manufacturing of complex components and the construction of digital platforms.

Keywords: Additive-subtractive integrated manufacturing; Digital collaboration; Collaborative design; Hybrid manufacturing; Lightweight components

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1. Introduction

Additive manufacturing and subtractive manufacturing are two distinct manufacturing methods. The former is a technology for fabricating three-dimensional solid parts by depositing materials layer-by-layer. The latter is a technology for obtaining parts with required shapes and dimensions via tool cutting and grinding. Additive manufacturing boasts advantages such as high design freedom, high material utilization and strong

capability for personalized customization. Nevertheless, products produced by this manufacturing technology suffer from defects including large surface roughness and insufficient dimensional accuracy ^[1]. Parts processed by subtractive manufacturing feature high precision and excellent surface quality, yet subtractive manufacturing has difficulties in machining components with complex internal flow channels and hollow topological structures. Additive-subtractive integrated manufacturing is a new technology that combines product design, software control, additive manufacturing and subtractive manufacturing. It first accomplishes near-net-shape blanks by additive manufacturing, and then conducts finish-machining on key mating surfaces through subtractive manufacturing, or performs component forming by alternating additive and subtractive procedures, which can make up for the defects of a single manufacturing process ^[2]. At present, there still exist several problems in the development of additive-subtractive integrated manufacturing, mainly manifested as mutual independence among design models, additive-forming simulation and subtractive-machining process data; failure to feed back additive-forming deformation and residual stress to design links in advance; lack of digital collaborative means for additive-blank allowance planning and unified machining references; delayed information interaction among designers, process engineers and manufacturing units, and prolonged R&D cycles caused by repeated iteration ^[3-6]. The organic integration of additive-subtractive integrated manufacturing and digital collaborative design, as well as the construction and improvement of the hybrid theoretical system for additive-subtractive manufacturing processes, are of great significance for improving product production efficiency and machining accuracy, and cutting production costs and environmental pollution.

2. Construction of theoretical system for digital collaborative design of additive-subtractive integrated manufacturing

This paper constructs the theoretical system from three layers: basic-theory layer, technical-support layer and operation-collaboration layer. The three layers support one another from bottom to top and form a complete logical framework.

2.1. Basic-theory layer

The basic-theory layer serves as the foundation of the whole theoretical system, including hybrid-manufacturing-process theory and digital-collaboration theory.

- (1) Hybrid-manufacturing-process theory for additive-subtractive manufacturing: In the additive-subtractive hybrid-manufacturing process, additive-manufacturing tool-paths are first generated to produce three-dimensional solid parts; afterward, parts are machined and revised following subtractive-manufacturing workflows until design requirements are met.
- (2) Digital-collaboration theory: Digital collaborative design requires support from a collaborative-design platform. Different professional teams shall formulate data-exchange rules for heterogeneous systems, construct multi-agent information-interaction mechanisms, clarify configuration modes of digital elements, and jointly build a multi-professional collaborative platform to resolve information silos among departments and systems ^[7,8].

2.2. Technical-support layer

The technical-support layer constitutes the fundamental guarantee for the practical application of the

theoretical system, covering four types of technologies and one standard system.

- (1) MBD-based three-dimensional model technology: With this technology, designers can integrate dimensional tolerances, material information, additive-manufacturing process parameters and subtractive-machining requirements, and comprehensively analyze part-design requirements.
- (2) Multi-scale numerical-simulation technology: Designers can adopt this technology to carry out thermal-mechanical simulation of additive forming, structural-mechanical simulation and NC cutting simulation, and predict defects such as warping deformation, machining interference and stress concentration in advance.
- (3) Heterogeneous-software digital-integration technology: Researchers can leverage this technology to open-up data interfaces among 3D-design software, additive-slicing software, CAM programming software and simulation platforms, and realize the sharing of design-model information.
- (4) Digital-twin and process-monitoring technology: Various business teams can utilize this technology to collect real-time operation data of additive-subtractive equipment, and understand the mapping relationship between physical-manufacturing units and digital models.
- (5) Unified-data-standard system: Professional teams shall establish unified standards for digital collaborative design, including standards for model format, process data, as well as storage and transmission of inspection data, so as to ensure cross-platform information compatibility^[9].

2.3. Operation-collaboration layer

The operation-collaboration layer acts as the principal module for practical application of the theoretical system, consisting of four parts: design-simulation collaboration, machining-procedure collaboration, business-subject collaboration, and process-quality-inspection collaboration.

- (1) Collaboration between structural design and process simulation

In the collaboration between structural design and process simulation, designers build three-dimensional part models, and then optimize the models by means of topology optimization and lightweight-optimization technologies. Next, the optimized models are imported into the additive-simulation system to predict residual stress and deformation magnitude generated in additive forming^[10]. According to simulation results of additive processes, designers can adjust structures and optimize support layouts in a timely manner. The adjusted models are then imported into the subtractive-cutting simulation system to examine the accessibility of finish-machining zones and improve the feasibility of design schemes^[11].

- (2) Collaboration between additive-forming and subtractive-machining procedures

Designers and engineers shall make use of digital collaborative platforms to communicate and formulate additive-subtractive machining procedures according to part purposes and functions. In terms of implementation schemes, lightweight components are manufactured by producing blanks via additive manufacturing and finish-machining key mating surfaces by subtractive manufacturing; components with complex structures and high-precision requirements adopt the scheme of “alternating additive-subtractive machining”^[12,13].

- (3) Multi-business-subject collaboration

At the level of business collaboration, designers, engineers and manufacturing personnel can make use of digital collaborative-design platforms to efficiently transmit information generated in the design process, conveniently carry out mutual review and comment, and ensure orderly collaborative-design work of all professional teams.

(4) Collaboration between manufacturing process and quality inspection

The digital collaborative platform associates additive-subtractive machining-trajectory data with three-dimensional inspection models. After hybrid machining of parts, the platform automatically performs 3D-scanning inspection. Measured-deviation data are fed back to the design end and machining end, providing references for subsequent optimization of component-design allowances and additive-manufacturing process parameters, and realizing closed-loop optimization.

3. Analysis of the internal mechanism of digital collaborative design in additive-subtractive integrated manufacturing

The essence of the collaboration mechanism is a multi-link closed-loop feedback mechanism driven by data. This paper decomposes it into three dimensions: information-transmission mechanism, element-matching mechanism and full-process closed-loop-iteration mechanism.

3.1. Information-transmission mechanism

To realize two-way information transmission, this paper builds two-way information channels for the digital collaborative platform relying on unified MBD models. Geometry information and material information are transmitted from top to bottom, while manufacturing information, including forming deformation, machining interference, and dimensional out-of-tolerance, flows back from bottom to top.

3.2. Matching mechanism for digital-resource elements

Manufacturing-related digital elements include model resources, simulation computing power, process knowledge, machining equipment and human resources^[14]. In accordance with the structural complexity and machining-precision requirements of different parts, this paper proposes different combination modes for digital-resource elements. For large-size lightweight special-shaped automotive components, the collaborative platform allocates higher simulation computing power to satisfy multi-condition thermal-mechanical coupling calculation requirements. For small-sized precision components, the collaborative platform shall focus on optimizing reference collaboration for additive-subtractive manufacturing and tool-path collaboration for finish machining. Dynamic element matching balances R&D costs, machining efficiency and forming quality.

3.3. Full-process closed-loop-iteration mechanism

To improve product-manufacturing quality and efficiency, this paper puts forward a closed-loop-iterative digital-collaborative-design workflow: initial modeling → prediction of simulation-induced defects → planning of additive-subtractive process schemes → hybrid manufacturing by equipment → three-dimensional quality inspection → deviation-data analysis → reverse optimization. Data generated in each of the above-mentioned links are uploaded to the digital collaborative platform. Professional teams can adopt big-data-analysis technologies to analyze and solve problems existing in design schemes so as to enhance design quality^[15].

4. Case analysis: Digital collaborative design for additive-subtractive integrated manufacturing of lightweight special-shaped automotive load-bearing components

4.1. Case overview

This paper takes the design of lightweight special-shaped automotive load-bearing components as a research case. Such components bear vehicle-body loads, require internal hollow topological structures, and have high external dimensional-machining-precision requirements. However, it is difficult to realize high-precision machining of complex structures merely by additive manufacturing or subtractive-manufacturing schemes. Therefore, an additive-subtractive integrated-manufacturing scheme is proposed: metal additive manufacturing is first adopted to produce component blanks, and then five-axis CNC machine tools are used for finish-machining of external mating surfaces.

4.2. Implementation path of digital collaborative design

The digital collaborative platform integrates business modules covering design, simulation, additive-manufacturing processes and NC programming, providing support for digital collaborative design.

(1) Construction of unified MBD digital model

In the modeling phase, designers utilize 3D-design software to build the MBD model of components, including three-dimensional structural drawings, material parameters and tolerance requirements, and upload the model to the digital collaborative platform.

(2) Collaborative optimization of structural design and additive-manufacturing simulation

In the process-simulation phase, engineers export MBD models via information-model-management tools on the digital collaborative platform, simulate metal-additive-manufacturing schemes for such models, predict temperature fields, stress distribution and deformation trends in the machining process, and judge whether simulation results satisfy design requirements. In case of unsatisfactory simulation results, engineers feed simulation data back to the design end via feedback tools of the platform. Designers adjust structural layouts in a targeted manner until simulation results meet design requirements.

(3) Collaboration of additive-subtractive procedures and intelligent allowance planning

For additive-subtractive machining procedures, professional teams formulate standards for additive forming and subtractive machining of lightweight automotive components relying on models and simulation data from the digital collaborative platform, and determine process routes (additive forming of blanks → stress-relief heat treatment → finish-machining of flanges and pin shafts). In view of deformation risks arising from additive-subtractive machining, business teams introduce artificial intelligence into the process-simulation system. The system can automatically plan machining allowances according to the latest simulation data until simulation results meet the expectations of design schemes.

(4) Online collaboration between additive-manufacturing processes and NC machining

In the collaboration link between additive manufacturing and NC machining, additive-manufacturing engineers and NC engineers analyze design drawings together on the digital collaborative platform, and communicate process-related problems in the connection between blank forming and finish machining.

(5) Closed-loop feedback of machining and inspection

After component machining, engineers adopt 3D-scanning equipment to detect component geometric-surface data, upload inspection data to the collaborative platform, and compare deviations between inspection data and design models. Meanwhile, the digital collaborative platform incorporates deviation data into the process-knowledge base for design and allowance optimization of subsequent lightweight components

of the same type, forming a complete closed loop.

4.3. Implementation effects

Practice shows that design schemes obtained via the digital collaborative platform achieve better quality, which is mainly reflected in fewer trial-production times for lightweight components; a sharp drop in component scrap events caused by inconsistent references and unreasonable allowances; internal and external dimensional precision meeting design indexes; complete retention of internal topological structures. The technological level of additive-subtractive hybrid manufacturing is effectively improved.

5. Conclusion

To sum up, conforming to the development trend of additive-subtractive integrated manufacturing, constructing the theoretical system of digital collaborative design can open up full-process data links covering design, simulation, additive forming and subtractive finish machining, and solve pain points of conventional serial-mode manufacturing such as model separation, reference misalignment and repeated process trial-production. In the future, manufacturing enterprises and design institutes shall establish digital-oriented concepts, adopt digital-twin and artificial-intelligence technologies, actively build digital collaborative-design platforms for additive-subtractive integrated manufacturing, strengthen research on automatic process planning for additive-subtractive manufacturing and cross-enterprise industrial-chain collaborative manufacturing, accelerate the digital-upgrading process for manufacturing of complex parts, and further improve part-production efficiency and quality.

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