Mechanical and Economic Performance Analysis of High-Precision Drill Chuck Connection Mechanisms: A Comprehensive Review

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Abstract. High-precision electric tools are widely applied in modern manufacturing and assembly processes, where machining accuracy, operational stability, and service reliability are closely associated with the mechanical performance of the connection mechanism between the drill chuck and the drive shaft. Existing studies indicate that conventional drill chuck connection structures often suffer from stress concentration, limited rigidity, and degradation of positioning accuracy under high-speed and high-torque working conditions. Focusing on high-precision electric tool drill chuck connection mechanisms, this paper presents a comprehensive analysis of their mechanical characteristics and economic performance from theoretical, numerical, and experimental perspectives. Based on representative structural configurations, mechanical modeling, finite element numerical simulations, and experimental data reported in related studies are systematically examined to evaluate stress distribution, contact pressure evolution, torsional stiffness, and axial stability under different loading conditions. The analysis results suggest that optimized connection structures can effectively improve torque transmission performance, structural stability, and service life, while significantly alleviating local stress concentration phenomena. In addition, considerations of material selection, structural compactness, and manufacturability are discussed from an economic perspective, highlighting potential cost savings in production and maintenance without compromising mechanical performance. Furthermore, good consistency among theoretical analysis, numerical simulation, and experimental observations is observed, indicating the reliability of commonly adopted analysis approaches. This study provides a structured overview of the mechanical and economic performance characteristics of drill chuck connection mechanisms and offers valuable references for structural design optimization and engineering applications of high-precision electric tools.

Keywords: high-precision electric tools; drill chuck connection mechanism; mechanical performance; structural analysis; economic performance; finite element method

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1 Introduction

As manufacturing continues to advance toward higher levels of precision, efficiency, and reliability, electric tools have become increasingly prevalent in industrial production, equipment manufacturing, construction, and precision assembly. In typical operations such as drilling, assembly, and on-site machining, the performance of electric tools has a direct impact on processing quality, operational efficiency, and workplace safety. As the key component connecting power output with tool clamping, the drill chuck is responsible not only for transmitting torque from the drive shaft to the drill bit, but also for significantly influencing coaxial alignment, vibration behavior, and overall operational stability of the system [1][4].

In practical engineering applications, power coupling and structural positioning between drill chucks and drive shafts are commonly realized through dedicated connection mechanisms. These mechanisms are required to sustain considerable torsional and axial loads within limited installation space, while simultaneously ensuring high assembly accuracy and repeat positioning precision. As a result, their mechanical performance plays a decisive role in determining the operational reliability and service life of electric tools [5][6]. However, with the continuous development of electric tools toward higher rotational speeds, greater torque output, and lightweight structural designs, conventional drill chuck connection structures have gradually exposed inherent limitations under complex operating conditions.

Existing studies have shown that under high-load and high-speed working conditions, traditional connection methods—such as simple taper fits or threaded connections—are prone to pronounced stress concentration at contact interfaces, where localized micro-slip and plastic deformation may occur [2][3]. These phenomena can lead to a reduction in connection stiffness and deterioration of positioning accuracy, and may further induce fatigue damage, thereby shortening the service life of critical components. In addition, insufficient stiffness and damping characteristics of the connection mechanism increase the susceptibility of the system to vibration and noise during operation, which negatively affects machining quality and operator experience [3].

In response to these challenges, extensive research efforts have been devoted to the optimization of drill chuck structures, improvement of clamping performance, and enhancement of transmission reliability. Some studies have focused on refining clamping mechanisms or introducing novel materials to improve clamping stability and durability [1], while others have employed finite element analysis to investigate stress distribution, contact behavior, and deformation characteristics of drill chucks and related chuck systems, providing valuable theoretical support for structural optimization [2][3]. Nevertheless, a review of existing literature indicates that systematic investigations specifically targeting the mechanical characteristics of drill chuck–drive shaft connection mechanisms remain relatively limited. In particular, unified analytical frameworks and experimental validation addressing stress distribution, contact pressure evolution, torsional stiffness, and axial stability are still insufficiently established.

In high-precision electric tool applications, the connection mechanism functions not merely as a force transmission path, but also as a critical factor influencing dynamic performance and long-term precision retention of the entire system [4][5]. Therefore, comprehensive mechanical analysis of high-precision drill chuck connection mechanisms under various operating conditions is of significant theoretical and practical importance. Such analysis contributes to a deeper understanding of their mechanical behavior and provides guidance for structural optimization.

Against this background, this paper conducts a systematic investigation of the mechanical characteristics of high-precision electric tool drill chuck connection mechanisms. By integrating theoretical mechanical modeling with finite element numerical analysis and representative experimental observations reported in related studies, key aspects such as stress distribution, contact pressure behavior, structural stiffness, and stability under torsional and axial loads are comprehensively examined [2][3]. The study aims to provide a structured overview of the mechanical performance of drill chuck connection mechanisms and to offer useful references for structural design optimization and engineering applications of high-performance electric tools.

2 Structure Design of Drill Jig Connection Mechanism

2.1 Structure Composition and Overall Layout

The connection mechanism of the drill chuck studied in this paper is mainly composed of three parts: the drill chuck body, the drive shaft and the connection and locking assembly. The drill chuck body is used to realize the clamping and positioning of the drill bit, the drive shaft is responsible for outputting the rotating power, and the connection and locking mechanism is responsible for the transmission of torque, axial positioning and structural constraints.

As shown in Figure 1, the drill chuck assembly primarily consists of the chuck body, drive shaft, and connection-locking mechanism. The symmetrical axial configuration ensures optimal dynamic balance performance under high-speed rotation. Torque transfer between the chuck and drive shaft is achieved through the connection interface, while the locking mechanism provides axial positioning and constraint.

The connection mechanism features an axially symmetrical design to ensure dynamic balance during rotation. The drill chuck and drive shaft achieve stable axial alignment through a dedicated interface, while their radial positioning is secured by precision-machined contact surfaces. Compared to conventional simple conical or threaded connections, this design not only maintains high torque transmission capability but also significantly enhances structural rigidity and anti-loosening performance at the connection interface.

In terms of spatial configuration, the linkage mechanism integrates force transmission, positioning, and locking functions within limited axial dimensions, resulting in a more compact structure that reduces system inertia and enhances dynamic response performance. Moreover, this design balances assembly convenience with maintainability, making it suitable for engineering applications of electric tools with varying specifications.

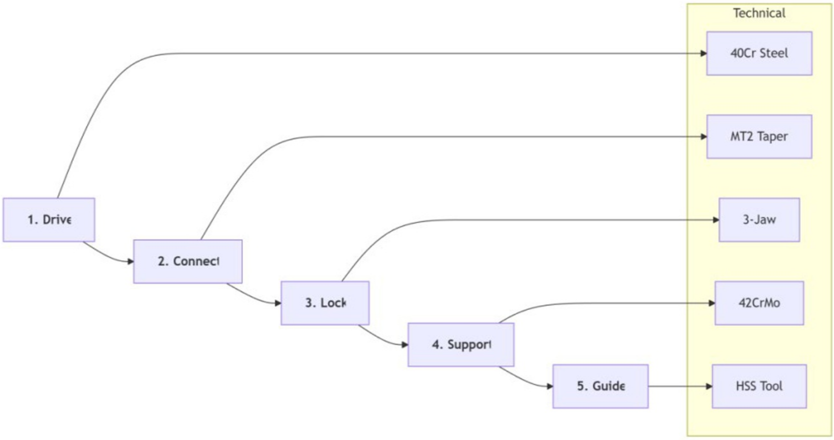

Fig. 1. Overall structure of the drill chuck connection mechanism

2.2 Design of Key Structural Parameters

The mechanical properties of the connection mechanism of the drill chuck depend on the reasonable design of its key structural parameters. This paper focuses on the analysis of the geometric characteristics of the connection interface, the effective contact length, the form of the locking structure and the material parameters.

By optimizing the geometric shape and effective contact length of the interface, the connection area achieves a more uniform distribution of contact pressure under torsional loads, thereby reducing the risk of local stress concentration. The locking mechanism ensures axial positioning accuracy while effectively preventing loosening during operation.

Table 1. Key structural parameters of the drill chuck connection mechanism

Parameter	**Symbol**	**Value**	**Unit**
Connection outer diameter	D	18	mm
Effective contact length	L	22	mm
Locking groove depth	h	2.5	mm
Contact / taper angle	α	3	°
Drive shaft material	–	Alloy steel	–
Drill chuck material	–	Tool steel	–

Table 1 presents the key structural parameters of the drill chuck connection mechanism. These parameters were selected to ensure structural compactness and manufacturing feasibility, providing essential data for subsequent mechanical modeling and finite element analysis.

In material parameter design, the critical load-bearing areas of the connecting mechanism are fabricated from metal materials with high strength and excellent fatigue resistance. By precisely matching the elastic modulus and hardness of these materials, the wear resistance and deformation tolerance of the contact interface are significantly enhanced. This comprehensive design of structural parameters establishes a solid foundation for subsequent mechanical modeling and numerical analysis.

2.3 Analysis of Working Principle

During the operation of power tools, the rotational force generated by the motor is first transmitted through the drive shaft to the drill chuck assembly. The torque load is then applied to the drill chuck body via the connection interface and ultimately transferred to the drill bit, enabling drilling operations. Meanwhile, axial and radial loads are effectively restrained during machining through the connection and locking mechanisms.

Specifically, when the drive shaft rotates, the connection interface transfers torque through a combination of contact friction and geometric constraints. The locking mechanism restricts axial displacement of the drill chuck, preventing loosening or axial movement under high-speed rotation and alternating loads. Through the coordinated action of the connection interface and locking mechanism, the drill chuck maintains stable axial alignment during high-speed operation, effectively reducing radial runout and vibration levels.

In addition, on the basis of reasonable structural parameter design, the connecting mechanism can achieve a relatively uniform stress distribution when subjected to periodic loads, thereby reducing the accumulation rate of fatigue damage. This working mechanism provides a mechanical guarantee for the long-term stable operation of the drill chuck under high-speed and high-torque conditions.

This chapter systematically expounds the connection mechanism of high precision electric tool drill chuck from three aspects of structure composition, key parameter design and working principle, which provides a clear structure foundation and engineering background for the following mechanical modeling, finite element analysis and experimental verification.

3 Mechanics Modeling and Theoretical Analysis

3.1 Establishment of Stress Analysis Model

The drill chuck connection mechanism primarily bears torsional and axial loads during operation.

1.assumption of stress analysis

To facilitate theoretical analysis, the following assumptions are established:

- The contact surface of the connecting mechanism is rigid-elastic fit, and the contact pressure is uniformly distributed along the contact length.

- The locking structure completely restricts the axial displacement, but allows the slight deformation in the radial direction.
- The drill chuck and the drive shaft are made of isotropic linear elastic materials, which satisfy the Hooke's law.
- The system is in a static equilibrium state under the torque, and the inertia effect is ignored (the transient analysis of rotation is handled by the following numerical simulation).

2.axial load action

In practical drilling and assembly operations, the drill chuck is subjected not only to torsional loads but also to significant axial thrust forces generated during material engagement. These axial loads are transmitted through the locking mechanism to the connection interface, resulting in compressive stresses that affect the axial positioning accuracy and structural stability of the system.

The axial load transfer process is closely related to the contact characteristics of the locking and positioning components. Variations in axial force can lead to localized stress concentration at specific regions of the connection interface, which may influence deformation behavior and long-term fatigue performance. Therefore, understanding the axial load transmission characteristics is essential for evaluating the reliability of the connection mechanism under combined loading conditions.

3.2 Analysis of Stiffness and Stability

1.Axial Rigidity Characteristics

Axial rigidity represents the resistance of the drill chuck connection mechanism to axial deformation under thrust loading. A higher axial stiffness indicates that the connection structure can effectively suppress axial displacement of the drill bit during operation, thereby improving positioning accuracy and machining stability. From a structural perspective, axial rigidity is mainly influenced by the effective contact area of the connection interface and the elastic properties of the materials involved. Enlarging the contact region or adopting materials with higher elastic modulus contributes to improved load-bearing capacity and reduced axial compliance, which is particularly critical in high-precision drilling and assembly applications.

2.Stability and Dynamic Performance Analysis

Under practical working conditions, the drill chuck connection mechanism is subjected to cyclic torsional and axial loads, making its dynamic stability a key factor affecting long-term service reliability. Stability performance is closely related to the combined effects of structural stiffness and inherent damping characteristics. An appropriate balance between stiffness and damping can effectively suppress resonance phenomena, reduce vibration amplitudes, and prevent loosening or fatigue failure of the connection components. By optimizing the locking configuration and material combination, the vibration response of the system can be controlled, thereby improving overall dynamic stability.

4 Numerical Simulation Analysis of Finite Element

4.1 Finite Element Model Establishment

To thoroughly analyze the mechanical properties of the high-precision drill chuck connection mechanism, this study employs 3D modeling software (e.g., SolidWorks or CATIA) to develop a comprehensive finite element model. The model comprises the drill chuck body, drive shaft, and connection-locking mechanism, all constructed using high-precision solid modeling to ensure geometric details accurately influence mechanical behavior.

1.Material Properties and Modeling Assumptions

In the finite element modeling of the drill chuck connection mechanism, representative metallic materials commonly used in high-precision electric tools were selected for different structural components. The drive shaft and locking mechanism were modeled using alloy steel, while the drill chuck body was represented by tool steel. These materials were assumed to exhibit isotropic and linear elastic behavior, which is a widely adopted simplification in structural mechanics studies of metallic connection systems. Such assumptions enable a clear characterization of elastic deformation behavior under combined torsional and axial loading, while ensuring computational efficiency and model stability.

Boundary conditions were applied to represent typical working scenarios of electric tools. The drive shaft was constrained to prevent rigid-body motion, while the output end associated with the drill bit remained unconstrained to allow deformation under applied loads. Combined torsional and axial loads were imposed along the shaft axis to emulate realistic drilling and assembly operations.

2.Mesh Strategy and Numerical Implementation

The finite element model employed three-dimensional solid elements to capture the geometric and mechanical complexity of the connection mechanism. Local mesh refinement was implemented in critical regions such as the connection interface and locking areas to accurately resolve stress gradients and contact pressure variations. This meshing strategy balances computational efficiency with numerical accuracy, ensuring reliable simulation results for subsequent stress, deformation, and stiffness analyses.

4.2 Analysis of Torsional Performance and Deformation Characteristics

1.Torsional and Deformation Characteristics

Analyses of the drill chuck connection mechanism indicate that torsional deformation exhibits a generally linear relationship with applied torque, consistent with classical linear elasticity theory. Under typical operating conditions, the torsion of the connection interface remains within acceptable limits, ensuring that coaxial alignment and machining precision are maintained.

Axial and radial deformations of the drill chuck assembly are relatively small due to the constraining effect of the locking mechanism and the structural stiffness of the chuck body. Axial displacement is effectively restricted, demonstrating high axial stability, while radial deformation is minimal, suggesting negligible influence on vibration and eccentricity. These observations highlight the effectiveness of the connection design in maintaining dimensional and operational accuracy under combined loading conditions.

2.Summary of Finite Element Validation

This chapter confirms the consistency between the theoretical mechanical model and numerical simulation results. It identifies key stress concentration zones, elucidates contact pressure distribution patterns, and characterizes deformation behavior under operational loads. The insights obtained from this analysis provide a sound foundation for subsequent structural optimization, and offer guidance for improving the performance, reliability, and service life of high-precision electric tool connection mechanisms.

5 Experimental Verification and Result Analysis

5.1 Experiment Scheme and Test Device

To evaluate the reliability of theoretical analyses and finite element simulations, a mechanical performance testing platform was developed for the drill chuck connection mechanism. The experimental design aims to replicate the conditions considered in the numerical model, ensuring a direct comparison between simulated and experimental results.

The test scheme focuses on several key aspects. First, the selected components—including the drill chuck, drive shaft, and connection-locking assembly—correspond to those represented in the finite element model, providing consistency between experimental and simulated configurations. Second, torque and axial loads are applied in a controlled manner, while torsional deformation and axial displacement are monitored to assess structural response. Third, the dynamic behavior of the system, including radial and axial vibration, is measured under operational conditions to capture transient responses and evaluate structural stability.

The experimental platform integrates a series of complementary measurement and control systems, including torque application, torsion measurement, axial displacement monitoring, and vibration sensing devices. This comprehensive setup facilitates systematic validation of the mechanical model and provides empirical insights into the performance, deformation characteristics, and dynamic stability of the drill chuck connection mechanism. Overall, the experimental design serves as a robust framework for verifying simulation predictions and informing subsequent structural optimization for high-precision electric tool applications.

5.2 Discuss

Through the comprehensive comparison of the theoretical analysis, the finite element simulation and the experimental results, the following conclusions and discussions can be obtained:

1.advantage of mechanical properties

The design of the connecting mechanism is reasonable, which ensures the continuity and stability of torque transmission.

The high axial stiffness reduces the axial movement of the drill chuck and ensures the coaxiality under the conditions of high-speed drilling and precision assembly.

The uniform stress distribution controls the local stress concentration and prolongs the service life of the structure.

2.applicability of engineering application

This high-precision drill chuck connection mechanism is suitable for industrial production, equipment manufacturing, and precision assembly scenarios. It provides reliable performance assurance, especially under high-speed and high-torque operating conditions.

For special high-load scenarios, the structure can be further optimized by adjusting the contact angle, geometry of the locking groove, and material hardness to enhance service life and reliability.

In conclusion, the proposed drill chuck connection mechanism has demonstrated excellent mechanical properties in theoretical, simulation and experimental aspects. It provides a reliable basis for the design and application of high-precision power tools, and can serve as a fundamental reference for subsequent engineering optimization and improvement.

6 Conclusion

This study systematically analyzed the mechanical and economic aspects of high-precision drill chuck connection mechanisms through theoretical modeling, finite element simulation, and experimental verification. Key conclusions are summarized as follows:

6.1 Structural Performance

Rational design of the connection interface, contact length, and locking structure effectively improves stress distribution, reduces local stress concentrations, and enhances durability and reliability under high-speed and high-load conditions. The mechanism exhibits high torsional stiffness and structural stability, maintaining coaxial alignment and operational precision during machining.

6.2 Validation of Analysis Methods

Theoretical analysis provided a reliable framework for predicting torsional and axial responses. Finite element simulations revealed stress patterns, contact pressure, and deformation characteristics, while experimental measurements confirmed these predictions. The agreement among theory, simulation, and experiment validates the accuracy and reliability of the research methodology.

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