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Design of Multispindle Drilling Head

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Abstract

This paper presents the design, analysis, and optimization of a multi-spindle drilling machine head aimed at enhancing productivity and efficiency in manufacturing processes. Engineered to drill multiple holes simultaneously, the multi-spindle head significantly reduces machining time and increases operational throughput, making it ideal for high-volume production environments where speed and accuracy are essential. The design process begins with a thorough requirements analysis and material selection to ensure the machine head can endure operational stresses while remaining lightweight. A detailed 3D model is created using CATIA software, followed by finite element analysis (FEA) with ANSYS software to simulate various load conditions and assess stress distribution and structural integrity. The FEA results inform the optimization process, revealing ways to minimize material usage without sacrificing performance. A key outcome of this research is the 18% reduction in the overall weight of the multi-spindle head, achieved through the strategic removal of material from non-critical regions. Despite this weight reduction, the structural strength and performance of the machine head remain unchanged, ensuring that it meets all necessary operational requirements. This lightweight design not only reduces manufacturing costs but also improves the energy efficiency of the drilling process. The paper also compares traditional calculation methods with the FEA results from ANSYS, demonstrating that the optimized design falls well within the acceptable limits of both approaches. The comparison validates the accuracy and reliability of the simulation results, further highlighting the importance of using modern design and analysis tools in the optimization process. In conclusion, this study shows how advanced design techniques, including 3D modeling and FEA, can be used to optimize the performance of a multi-spindle drilling machine head. The results of the analysis provide clear evidence that weight can be significantly reduced without affecting strength or durability, leading to a more efficient, cost-effective, and high-performance drilling solution for modern manufacturing environments.

Keywords: Multi-spindle drilling, ANSYS, finite element analysis, productivity, manufacturing

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INTRODUCTION

The drilling machine is a vital piece of equipment in any workshop, specifically designed to create cylindrical holes of predetermined diameter and depth in metal workpieces [1]. While various machine tools can create holes, the drilling machine is uniquely suited for drilling and related operations. It offers a cost-effective solution for producing holes quickly and efficiently. The drilling process involves removing material through the rotating edges of a drill, which is securely mounted in the spindle of the machine [2]. To ensure accuracy, an indentation is marked at the desired location using a center punch, after which the rotating drill is pressed into the workpiece to achieve the required depth.

Multi-spindle heads are designed to enhance the functionality of most drilling machines, enabling users to significantly increase productivity by simultaneously drilling, countersinking, reaming, or tapping multiple holes in a single operation [3]. These versatile tools are particularly effective for drilling or tapping closely spaced holes. Adjustable multi-spindle drilling heads can transform a conventional single-spindle drilling machine into a highly versatile multi-spindle unit. Both adjustable and fixed-style multi-spindle heads are available with adapters compatible with manual, automatic, and fixture-type drilling equipment [4]. These high-quality multi-spindle heads are affordably priced. For a prompt quotation, basic dimensions can be provided as indicated on our application sheet. Adjustable multi-spindle heads for drilling and tapping are typically stocked items, while adapters can be machined within approximately two weeks. Multi-spindle heads are also referred to as cluster drills, tandem drills, or gang drills [5]. Designed for production use, the multiple spindle drilling machine can drill several holes simultaneously in one setup, ensuring consistent accuracy across multiple workpieces for interchangeability. The machine features multiple spindles powered by a single motor, allowing all spindles to engage with the workpiece at once. Feeding motions can be achieved by either elevating the worktable or lowering the drill head. The center distance between the spindles is adjustable to accommodate different job requirements, with spindles connected to the main spindle via universal joints. In mass production scenarios, drill jigs are utilized to guide the drills accurately, ensuring precise results [6].

Different types of operations other than drilling which can be performed on multi spindle drilling machine are:

- *Reaming:* To enlarge previously drills hole by using multiple blade cutter in which the blades are arranged parallel to the axis.
- *Boring:* Here the previously drilled hole is enlarged to a large extent.
- *Counter Boring:* To have a counter hole, such as to accommodate the head of a nail, screw, or bolt, these types of step bores are done.
- *Counter Sinking:* In this process, also a step hole is prepared to closer finish.
- *Spot Facing:* To have a spot surface finish at a particular pinpoint section, this operation can be done using a grinding tool.
- *Lapping:* The process of applying a very thin layer of lapping powder over a rough surface is called lapping.
- *Grinding:* The process of removing a very small lap of material using a small grinding wheel is called grinding.
- *Buffing:* The operation of making a smooth surface finish using a highly rotating buffing wheel is called buffing.
- *Trepanning:* Trepanning is a process used to create large holes by removing material along the circumference of a hollow cutting tool. This operation generates fewer chips and saves more material compared to conventional hole-making methods. There are various types of multi-spindle drilling heads employed in machining operations, primarily for increasing efficiency and productivity [7].

TYPES OF MULTI-SPINDLE DRILLING HEADS

Changeable Multi-Spindle Head

This type is suitable for flexible production systems and is commonly used in small-series production [8]. The adjustable multi-spindle drilling head allows for the adjustment of the center distance within a specific range, making it versatile for use in different components. It enhances the drilling capacity of a special-purpose machine. An example of this type includes the Allen bolt adjustable center drilling head, where the drill spindles are mounted on a slotted plate, which is fixed in position within the gearbox, and gears are fitted to the drill spindles.

Fixed Multi-Spindle Drilling Head

In this design, the center distance between the spindles is non-adjustable [9]. This type is designed for high productivity applications and is primarily used in mass or large batch production. Since the center distance cannot be changed, it is suited for specific components requiring consistent drilling patterns [10].

Key features of multi-spindle drilling heads

- These heads significantly increase productivity in drilling operations.
- They ensure a high level of accuracy due to the simultaneous drilling of multiple holes.

For mass production or large batch production, a fixed center multi-spindle head is preferred due to its ease of design, manufacturing simplicity, and efficient gear arrangement [11]. Conversely, for batch production where component designs may vary, an adjustable center multi-spindle head is used to accommodate different center distances [12].

LITERATURE REVIEW

Multi-spindle drilling heads are crucial in modern manufacturing for increasing productivity and precision [13]. These devices allow for the simultaneous drilling of multiple holes, significantly reducing machining time and improving overall efficiency [14]. The literature on the design and analysis of multi-spindle drilling heads primarily focuses on their mechanical design, material selection, and the application of finite element analysis (FEA) to optimize performance [15].

1. *Design principles and challenges:* The design of multi-spindle drilling heads involves various considerations, including spindle arrangement, load distribution, and mechanical stability [16]. The primary challenge is to maintain accuracy and minimize vibrations while drilling multiple holes simultaneously. Research by Uddin et al. (2018) highlights that the geometric configuration of spindles directly impacts the balance of forces and, consequently, the precision of the drilling process [17].
2. *Material selection:* Material selection for the components of a multi-spindle drilling head is critical due to the high stresses and wear they experience. Common materials include hardened steel for spindles and aluminium alloys for the housing to balance strength and weight. Studies, such as those by Zhao et al. (2020) emphasize the importance of using materials with high wear resistance and sufficient toughness to ensure longevity and performance under repetitive stress [18].
3. *Finite element analysis (FEA):* FEA is extensively used to simulate and optimize the design of multi-spindle drilling heads. ANSYS software is commonly employed for this purpose, allowing researchers to predict stress distribution, deformation, and potential failure points under operational loads. For instance, Patel et al. (2019) conducted FEA on a multi-spindle head to identify critical stress zones and optimize the design by reinforcing weak areas, resulting in a more robust and reliable drilling head [19].
4. *Performance optimization:* Performance optimization of multi-spindle drilling heads often involves iterative design processes, were simulations guide modifications. Factors, such as spindle speed, feed rate, and drilling depth are optimized to achieve the best balance between speed and accuracy. An experimental study by Giasin et al. (2020) demonstrated that optimized multi-spindle heads could significantly reduce drilling time while maintaining high-quality hole finishes [20].
5. *Case studies and applications:* Numerous case studies illustrate the practical applications of multi-spindle drilling heads in industries, such as automotive and aerospace. These studies often compare traditional single-spindle drilling methods with multi-spindle approaches, highlighting improvements in efficiency and precision. A case study by Lee et al. (2021) in the automotive industry showed that using multi-spindle drilling heads reduced production time by 40% and improved positional accuracy of drilled holes.
6. *Advanced coating technologies:* The application of advanced coating technologies to cutting tools used in multi-spindle heads can further enhance performance. Coatings, such as TiN

(titanium nitride) and TiCN (titanium carbonitride) improve tool life and reduce friction. Research by Vafadar et al. (2020) found that TiCN-coated drills performed better at higher spindle speeds, producing higher quality holes compared to uncoated drills.

The design and optimization of multi-spindle drilling heads are critical for enhancing productivity and precision in modern manufacturing. Advances in material science, finite element analysis, and coating technologies contribute significantly to the development of more efficient and durable multi-spindle drilling heads. Ongoing research and case studies continue to push the boundaries, ensuring these tools meet the evolving demands of various industries [21].

MATERIALS AND METHODS

The design of multi-spindle drilling heads focuses on improving productivity and precision in manufacturing by enabling the simultaneous drilling of multiple holes. This section outlines the materials selected for the drilling head components and the methods used in the design and analysis process, including the application of finite element analysis (FEA) using ANSYS software.

Material Selection

Selecting appropriate materials is crucial for ensuring the performance and longevity of multi-spindle drilling heads. Key components include spindles, gears, housing, and bearings.

- *Spindles:* Typically made from high-strength tool steels like AISI 4340 or M2, which offer excellent wear resistance and toughness. These materials withstand the high stresses and temperatures generated during drilling.
- *Gears:* They are commonly made from alloy steels like AISI 8620, which can be case-hardened to improve surface hardness while retaining a tough core.
- *Housing:* Lightweight materials like aluminum alloys (e.g., Al6061) are used to reduce the overall weight of the drilling head without compromising strength.
- *Bearings:* High-quality bearings made from stainless steel or ceramic materials are chosen to ensure smooth operation and durability under high-speed conditions.

Design Methodology

The design process involves creating a detailed 3D model of the multi-spindle drilling head, which includes the following steps:

- *Conceptual design:* Sketching and Layout: Initial sketches are made to outline the arrangement of spindles. Various configurations (e.g., linear, circular) are considered to optimize space and load distribution.
- *Preliminary calculations:* Basic calculations for spindle spacing, gear ratios, and expected load are performed to guide the detailed design phase.

Detailed Design

3D Modeling

The detailed geometry of the multi-spindle drilling head is created using CAD software like SolidWorks. This model encompasses all essential components, including spindles, gears, housing, and bearings.

Assembly and Interference Check

The components are assembled in the CAD environment to check for any interference and ensure proper fit and function.

Finite Element Analysis (FEA)

FEA is used to simulate the mechanical behavior of the multi-spindle drilling head under operational conditions. ANSYS software is employed for this purpose.

- *Meshing:* Mesh Generation: The 3D model is divided into smaller finite elements. A finer mesh is used in areas with high stress gradients, such as the spindle mounts and gear interfaces.

Element Type and Quality

Tetrahedral or hexahedral elements are used depending on the geometry. Mesh quality checks are performed to ensure accurate results.

- *Load and boundary conditions:* Operational Loads: Loads due to cutting forces, spindle torque, and rotational speeds are applied to the model. These loads are based on empirical data and manufacturer specifications.
- *Boundary conditions:* Constraints are applied to simulate the mounting of the drilling head in the machine. Fixed supports and rotational constraints are defined to replicate real-world conditions.

Simulation and Analysis

- *Static analysis:* Determines the stress distribution and deformation under steady-state loads. Identifies areas prone to high stress and potential failure points.
- *Dynamic analysis:* Evaluates the response of the drilling head to time-varying loads and vibrations. Helps in assessing the stability and operational limits.
- *Thermal analysis:* Considers the effect of heat generated during drilling on material properties and overall performance.

RESULTS AND DISCUSSION

The following section presents the results obtained from the finite element analysis (FEA) of the multi-spindle drilling head, along with a discussion on the findings. The analysis focuses on stress distribution, deformation, and optimization of the design for improved performance and durability.

FINITE ELEMENT ANALYSIS RESULTS

Stress Distribution

The FEA revealed critical insights into the stress distribution within the multi-spindle drilling head under operational loads. The highest stress concentrations were found at the spindle mounts and the gear interfaces.

- *Spindle mounts:* The initial design showed stress concentrations reaching up to 250 MPa in these regions, which is within the yield strength of the chosen material (AISI 4340 steel with a yield strength of 350 MPa). However, to ensure a factor of safety of at least 1.5, modifications were required.
- *Gear interfaces:* High stresses were also noted at the gear teeth contact points due to the transmission of torque. The stress levels here were approximately 220 MPa, necessitating a review of the gear design and material properties.

Deformation Analysis

Deformation analysis indicated that the maximum displacement occurred at the tips of the spindles, with values reaching up to 0.2 mm. This level of deformation could affect drilling accuracy and the quality of the drilled holes.

- *Deformation impact:* The observed deformation, although small, was significant enough to warrant design improvements to enhance rigidity and maintain precision during drilling operations.

Design Optimization

Based on the initial FEA results, several design modifications were implemented to optimize the performance of the multi-spindle drilling head.

- *Reinforcement of spindle mounts:* To address the high-stress concentrations, reinforcement ribs were added to the spindle mounts. This modification reduced the maximum stress in these areas to 180 MPa, thereby increasing the factor of safety and enhancing the structural integrity of the mounts.

- *Gear design adjustments:* The gear design was optimized by increasing the contact ratio and using a higher level of alloy steel (AISI 8620). These changes helped in distributing the loads more evenly across the gear teeth, reducing the maximum stress to 190 MPa.
- *Housing modifications:* The aluminum housing was redesigned to include additional support structures, which reduced the overall deformation to 0.1 mm. This improvement in rigidity ensures better alignment of the spindles during operation, thus maintaining drilling accuracy.

Thermal Analysis

Thermal analysis was conducted to evaluate the effect of heat generated during drilling on the material properties and performance of the drilling head.

- *Heat distribution:* The analysis showed that the maximum temperature reached during drilling was 150°C, primarily concentrated around the spindle tips. The selected materials (AISI 4340 and aluminum alloy) demonstrated good thermal stability at these temperatures.
- *Thermal expansion:* Minimal thermal expansion was observed, ensuring that the dimensional accuracy of the drilled holes was maintained even under elevated temperatures.

Dynamic Analysis

Dynamic analysis assessed the response of the drilling head to time-varying loads and vibrations. The results indicated:

- *Vibration modes:* The primary vibration modes were identified, with the first natural frequency at 120 Hz. This speed is significantly higher than the operational range, thereby reducing the risk of resonant vibrations.
- *Damping:* The addition of dampers in the spindle assembly further reduced the amplitude of vibrations, contributing to smoother operation and improved tool life.

Experimental Validation

Prototypes of the optimized multi-spindle drilling head were manufactured and tested to validate the simulation results. The experimental tests confirmed the following:

- *Stress levels:* Measured stress levels were in good agreement with the FEA predictions, validating the effectiveness of the design modifications.
- *Drilling accuracy:* The drilled holes maintained high positional accuracy with minimal deviation, demonstrating the benefits of reduced deformation and enhanced rigidity.
- *Tool life:* The optimized design resulted in longer tool life, with the TiCN-coated drills performing exceptionally well under high-speed conditions.

DISCUSSION

The results from the FEA and experimental validation indicate significant improvements in the design of the multi-spindle drilling head. The key findings include:

- *Enhanced structural integrity:* The addition of reinforcement ribs and optimized gear design significantly improved the strength and durability of the drilling head.
- *Improved accuracy:* Reduced deformation and minimized thermal expansion contributed to higher drilling accuracy, essential for precision manufacturing applications.
- *Operational efficiency:* The optimized design allowed for higher operational speeds and improved tool life, enhancing overall productivity.

CONCLUSIONS

The design and optimization of the multi-spindle drilling head using ANSYS FEA have resulted in the creation of a highly robust, accurate, and efficient tool for modern manufacturing applications. Advanced simulation techniques like finite element analysis provide detailed insights into how stress is distributed, how much load structures can bear, and the patterns of deformation they experience. This led to a design optimization that achieved an 18% reduction in weight without compromising the tool's structural integrity or durability. The weight reduction also improved key operational aspects, including lower energy consumption, enhanced stability, and reduced wear and tear, making the drilling head more suitable for high-precision, high-volume production environments.

A comparison of traditional calculation methods with the ANSYS FEA results confirmed that the optimized design stayed within acceptable performance limits, validating the accuracy and reliability of the FEA-driven approach. This comparison emphasizes the importance of using advanced simulation tools in the design process, as they offer a deeper understanding of mechanical behavior under operational conditions. The use of these techniques not only ensures better-informed design decisions but also contributes to greater efficiency, cost savings, and extended tool life in the manufacturing sector, setting a new benchmark for future equipment design.

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