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Vacuum Clamping Technology for Machining Thin-Walled Parts: A Review

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ABSTRACT

Thin-walled parts (TWPs) are characterized by lightweight and high strength, making them widely used in aerospace, automotive, and other fields. However, their low stiffness often leads to deformation and vibration during machining. To address this issue, vacuum adsorption fixtures (VAFs) have emerged as a key technology, utilizing negative pressure to generate a uniform clamping force. These fixtures simultaneously fulfill the functions of positioning, vibration suppression, and surface protection. This paper reviews the development of vacuum adsorption technology over the past decade, examining related technologies, structural innovations, and layout optimizations of typical vacuum adsorption fixtures. It classifies and analyzes the principles and characteristics of different fixtures, comparing and summarizing their mechanisms, advancements, advantages, and limitations. Finally, the challenges faced by vacuum adsorption fixtures and their future development trends are explored, providing a foundation for further research in this field.

KEYWORDS

Component; Thin-walled parts; Vacuum adsorption technology; Adsorption fixtures; Machining deformation control; Flexible support

1 Introduction

Thin-walled parts (TWPs) are widely used in aerospace, automotive, and other high-end manufacturing fields due to their lightweight and high-strength advantages. However, their low-stiffness characteristics make them highly susceptible to deformation and vibration under cutting forces, which becomes a bottleneck restricting machining accuracy and efficiency. Traditional mechanical fixtures have disadvantages such as concentrated contact stress and significant clamping deformation, making it difficult to meet the multiple requirements of positioning, vibration damping, and surface protection. Vacuum adsorption fixtures (VAFs) have gradually emerged as a key technology to address these challenges, leveraging the advantages of uniformly distributed negative pressure, non-contact support, and flexible adaptation.

Over the past decade, research in this field has evolved from early fixed support functions to closed-loop intelligent systems integrating sensing, control, and compensation. In 2014, Hu Fuwen's team pioneered the integration of CNC-built PLCs with matrix sensors to achieve millisecond-level fixture-machine tool coordination. In 2019, Zhang Shaokun et al. developed a real-time thickness estimation model using ultrasonic-vortex current composite sensing, significantly suppressing thickness fluctuations in mirror milling. After 2020, new materials and configurations—such as vacuum preloaded static pressure supports, rubber-damped flexible fixtures, and carbon-fiber-aluminum alloy composite structures—have continued to emerge, advancing fixtures from single-function deformation suppression to multi-dimensional optimization of surface quality, chatter suppression, and process parameter co-optimization.

However, existing research remains largely confined to ideal laboratory conditions, lacking systematic solutions for real-world challenges such as curved surface deformation, seal aging, measurement delays, and rapid switching between multiple part types in production environments. To address this gap, this paper systematically reviews the evolution of vacuum adsorption fixtures over the past decade in terms of intelligent control, structure-process integration design, and the application of new materials. It analyzes their advantages and limitations while providing insights into future directions for integrated technology development, aiming to establish a theoretical foundation and reference for high-precision manufacturing of thin-walled parts.

2 Evolution of supporting technologies

The significance of vacuum fixtures for thin-walled part machining has progressively evolved from purely "fixing" to an integrated functional chain encompassing sensing, supporting, and ultimately compensating. Over the past decade, technological advancements have followed two primary trajectories: first, the standardization and real-time information interface between fixtures and machine tools, and second, the coupling and synergy of the three processes—support, measurement, and control. The following presents a chronological review of pivotal studies to illustrate the evolutionary logic of this field, from intelligent sensing to closed-loop control and ultimately to zero-damage support.

2.1 Intelligent vacuum fixture integrated with CNC built-in PLC

In 2014, Hu Fuwen's research team proposed an innovative intelligent vacuum fixturing system, achieving intelligent fixture control through deep integration with the built-in PLC of a CNC machine tool. This study designed a matrix sensor-end-effector structure, with each unit combining suction cups and four proximity switches, enabling automatic workpiece contour recognition and triggering of the adsorption process. The key breakthrough of this research involved the development of a dedicated M-code (M90) based on the M64 CNC system, establishing an innovative mechanism for coordinated control between fixture operations and NC programs, thereby significantly enhancing machining process automation.

Theoretically, this research integrated static mechanics equations with a dynamic spring-damping model, quantitatively demonstrating for the first time the decisive influence of joint flexibility on system dynamic characteristics. This contribution provides a novel approach for vibration control in thin-walled part machining.

2.2 Closed-loop control scheme for thickness compensation in mirror milling

In the machining of aerospace thin-walled components, thickness control instability caused by workpiece deformation has long constrained accuracy improvement. Shaokun Zhang's research team has innovatively proposed a MSP-DOB composite control architecture to address the closed-loop oscillation problem resulting from measurement delay in mirror milling. This approach involves fusing ultrasonic and eddy-current sensor data to construct a real-time thickness estimation model, which significantly reduces information acquisition delay. The team designed a cascade controller system: the inner-loop DOB rapidly suppresses external perturbations (such as time-varying cutting forces) based on the estimated values, while the outer-loop MSP compensates for both measurement delay and model errors. Experimental results demonstrate that this method significantly improves thickness consistency, yielding a more concentrated error distribution and more stable machining performance.

2.3 Vacuum preloaded hydrostatic bearing

To address the challenge of high-precision machining of large thin-walled components in the aerospace industry, Mengfan Lu's research team proposes an innovative vacuum-preloaded hydrostatic support technology. This approach integrates vacuum adsorption force with a hydraulic liquid film to establish a non-contact support mechanism, thereby eliminating direct contact between the tool and workpiece. The study systematically completed the support head design, developed models for liquid film thickness and stiffness, and constructed a simplified experimental platform. Using a 6061 aluminum alloy thin plate, the research verified the effects of varying inlet pressures and vacuum preloading on milling depth, thickness consistency, and surface roughness. Experimental results demonstrate that this technique enhances machining accuracy while reducing surface roughness. This study provides an effective solution to the problems of scratches and deformation in thin-walled part machining. The theoretical model and experimental design establish a robust foundation for subsequent engineering applications.

As can be seen from the overview above, advancements in vacuum adsorption fixture technology have consistently pursued three primary objectives: real-time operation, non-invasive application, and high stiffness. Initially, this involved achieving millisecond-level interaction between the fixture and CNC systems. Subsequently, signal thickness was incorporated into closed-loop control, followed by further friction isolation through the implementation of a liquid film. Together, these three developments outline the trajectory toward achieving integrated "sense-control-support" functionality.

3 The multidimensional development of fixtures: from deformation suppression to surface quality enhancement

3.1 Deformation control and mechanical optimization

In the context of deformation control and mechanical optimization for thin-walled part processing, various research teams have proposed distinct solutions. In 2017, He Zedi's research team utilized a standard aluminum alloy hemispherical shell as their test specimen. By integrating the static force balance equation under negative vacuum pressure with classical thin shell theory, they derived an analytical expression for radial deflection in the contact area between the tapered suction device and the spherical shell. Furthermore, they developed a mathematical optimization model incorporating taper angle and negative pressure as design variables. Through finite element calibration of key coefficients, the team incorporated the dual variables of "taper angle-vacuum pressure" into constrained optimization, achieving micron-level machining deformation control.

In 2020, rather than restricting their analysis to ideal geometries, the Ju Kang team investigated low-stiffness, pure copper flat plates. They identified a previously overlooked source of error—the initial surface profile mismatch between the fixture and the workpiece. To address this issue, they developed a novel methodology: first employing sub-aperture interferometry to measure the three-dimensional surface profiles of both the workpiece and the suction cup, then importing the processed data into ABAQUS to construct a contact model incorporating both ideal and actual surfaces. Building upon Hertzian contact theory and thin-plate theory, they partitioned the entire domain into three distinct regions—the contact zone, the non-contact zone, and the peripheral overhanging zone surrounding the holes—and derived separate deformation functions for each segment. Static vacuum adsorption experiments validated the reduction in prediction error. Their research systematically demonstrates the critical influence of surface error on deformation distribution across the entire domain and introduces a compensation strategy based on position angle rotation optimization.

In 2024, Wenhao Xing's team expanded their research focus to aerospace skin applications. To address localized overhang collapse caused by pre-drilled holes in molds, they implemented a coupled finite element model incorporating the mold, skin, and sealing strips. Their verification demonstrated that adding sealing strips around the holes effectively suppresses millimeter-scale depressions, thereby advancing the deformation control strategy from parameter optimization to a structural compensation approach.

These three studies progressively advance machining deformation control from analytical optimization approaches to measurement-driven structural compensation schemes, thereby establishing a comprehensive technical pathway from theoretical development to engineering implementation for the mechanical optimization of vacuum adsorption fixtures for thin-walled components.

3.2 Structure-process integrated design of fixtures

Vacuum clamping technology has demonstrated a trend toward structure-process integration over the past decade. In 2014, T. V. Harini's research team introduced the "H-frame" vacuum fixture for aerospace aluminum alloy thin-walled frame components. By integrating cutting force prediction models with finite element static-dynamic analyses, the machining load paths were incorporated into the iterative optimization of the vacuum adsorption zone's mesh density during the fixture layout stage. Consequently, the fixture structure evolved from a passive carrier to an elastic component that actively participates in cutting force redistribution.

In 2017, Manzoor et al. proposed a reconfigurable flexible vacuum clamping system for thin-walled cylindrical shell parts. Through theoretical derivation, they established the response relationship between vacuum pressure, workpiece stiffness, and cutting parameters. The team conducted multifactor experiments on a CNC lathe, optimizing feed rate, depth of cut, and vacuum pressure using response surface methodology. They also performed inverse correction of the geometric dimensions for both the vacuum cavity and sealing groove. This study introduces the "flexible reconfigurable" concept into vacuum fixtures to reduce clamping time and minimize material waste.

In 2021, Ren Weiming's team proposed a "vacuum adsorption milling fixture" for high-speed milling scenarios involving ultra-thin pure copper discs. This fixture consists of a sealing groove, a vacuum generator, and an array of suction cups. Using finite element simulation methods, the team analyzed the deformation of thin-walled parts under the coupling effects of cutting force and residual stress evolution. The simulation results guided the optimization of suction cup arrangement and vacuum pressure. This fixture not only provides a flexible boundary for uniform adsorption but also functions as a damping element to suppress high-frequency vibrations. Consequently, the flatness error can be controlled at the micrometer level.

It is evident that the traditional sequence of structure followed by process for vacuum adsorption fixtures is gradually transitioning into a parallel iterative scheme, and the iterative mode of finite element simulation and field testing is maturing. However, this approach remains limited to a single workpiece family and steady-state vacuum conditions. Further research is necessary for future applications in machining complex curved surfaces of large, intricate thin-walled structures in aviation and aerospace, as well as in variable vacuum clamping.

3.3 New materials and special applications

In the development of vacuum adsorption fixtures, addressing the specific requirements of rubber damping, non-metallic thin-walled components, and titanium alloy complex machining parts, researchers have systematically investigated the synergistic optimization of material selection, structural topology, and process parameters.

In 2020, Rubio-Mateos et al. integrated the viscoelastic-elastoplastic damping properties of vulcanized rubber layers with vacuum adsorption functionality to develop a flexible vacuum fixture adaptable to complex surfaces. Using AA2024 aerospace skin as a test case, they experimentally demonstrated the relationship between rubber hardness, stiffness loss due to material removal, and chatter suppression through stability lobe diagrams. The researchers proposed and validated a surface roughness decomposition model that separates roughness into three components: theoretical geometric error (Rh), rubber elastic compression (Rr), and fixture-part relative displacement (Rf) for vibration source identification. Their findings demonstrate the effectiveness of rubber-based fixtures in chatter suppression, while revealing that hard rubber optimizes surface quality in high-speed milling applications.

Four years later, in 2024, Norfariza Ab Wahab's team systematically compared the effects of supported versus flat air channel configurations on surface quality and dimensional accuracy in end milling of non-metallic thin-walled parts, using a 6 mm acrylic sheet as the test material. Their findings demonstrated that the supported micro-groove structure maintained uniform adsorption at lower vacuum levels, thereby reducing edge chipping and surface ripples.

In 2025, Li Yongping's team optimized and iterated the machining process of ultra-thin-walled titanium alloy parts by improving adsorption force uniformity, fixture rigidity, and material selection. First, they implemented a gradient surface adsorption surface, optimized suction cup layout, and variable aperture design to enhance force field uniformity. Next, they utilized a high-strength aluminum alloy-carbon fiber composite structure to increase fixture rigidity while maintaining lightweight properties. Finally, finite element simulation verified that the optimized fixtures effectively reduced workpiece deformation, significantly improving shape accuracy and surface integrity.

In summary, from the flexibility of rubber damping to the low-damage characteristics of non-metallic thin-walled structures, to the progressive exploration of high-precision titanium alloy machining, vacuum adsorption fixtures have achieved continuous breakthroughs in the synergistic optimization of materials and structures. However, further validation and expansion are still required to meet the demands of multi-species, highly dynamic service conditions.

4 Current shortcomings

In the current development of vacuum adsorption fixtures, several critical challenges remain to be addressed. At the technical level, while the intelligent vacuum fixture proposed by Hu Fuwen's team demonstrates innovation, it imposes stringent requirements on workpiece surface flatness, exhibits a limited application range, and fails to investigate the long-term effects of dynamic vibration on clamping stability. The thickness compensation method for mirror milling introduced by Shaokun Zhang's team enhances thickness control accuracy; however, it heavily depends on the precision of system modeling, and its robustness against measurement delays and parameter variations in actual machining processes requires further validation. Similarly, the vacuum pre-pressure hydrostatic support technology developed by Mengfan Lu's team improves workpiece surface quality, but its experimental validation was conducted on a simplified three-axis platform. This approach does not adequately account for the applicability to complex surfaces or multi-axis linkage conditions, and the parameter optimization relies on empirical methods, lacking universal guidance.

In addressing deformation control and mechanical optimization, the mechanical model developed by He Zedi's research team fails to adequately account for workpiece face shape errors and eccentric clamping in practical applications. Additionally, the model does not consider the weakening effects of dynamic vibration caused by continuous turning on long-term stability. Ju Kang's team's algorithm depends on high-precision face shape data, yet the robustness of the method concerning online measurement latency and parameter drift remains unverified. Wenhao Xing's team's experimental work is confined to flat, small-scale three-axis platforms, and their model continues to assume rigid molds. Furthermore, there is no systematic evaluation of vacuum holding capacity and seal durability under complex curved surfaces and multi-axis conditions. The impact of seal aging and vacuum fluctuations on long-term accuracy has also not been examined.

In terms of fixture structure-process integration, the design of T. V. Harini's team exhibited high sensitivity to initial flatness in relation to sealing performance. Vibration stability was assessed solely through short-term modal analysis, without evaluating the cumulative effects of dynamic perturbations during continuous cutting. The experiments conducted by Manzoor T.'s team were limited to a single-diameter aluminum alloy shell and did not thoroughly investigate the sealing structure of the vacuum chamber or the strategy for rapid changeover between multiple species. The design by Weiming Ren's team focused primarily on disk-shaped parts and did not address the complex sealing challenges associated with shaped curved surfaces or multi-chamber vacuum passages. Additionally, the study lacked long-term data on vacuum stability in conjunction with thermal deformation.

Regarding new materials and special applications for fixtures, Antonio Rubio-Mateos' team's experiments were limited to small-scale prototypes and low-feed conditions in laboratory settings. The fixtures' performance and applicability require further verification, as vulcanized rubber may exhibit performance degradation under high temperatures and loads, potentially limiting its application in extreme machining conditions. Norfariza Ab Wahab's team studied only a single thickness and did not examine difficult-to-machine metals such as titanium alloys. Their research also lacked long-term wear analysis of the vacuum block and aging behavior of the seals. Additionally, they employed only static negative pressure without real-time adjustable or closed-loop control, making it difficult to adapt to workpiece warpage variations in mass production. Yongping Li's team's study focused solely on a single aerospace structural component as a case study and did not address rapid reconfiguration challenges in multi-variety, small-batch production. Thus, the broader applicability of this design remains uncertain.

In general, current research on vacuum adsorption fixtures remains primarily at the laboratory stage. When confronted with real-world workshop challenges such as surface deformation, seal aging, measurement delays, and multi-variety switching, there remains a lack of comprehensive, directly implementable solutions.

5 Conclusions

5.1 Research conclusions

Over the past decade, vacuum adsorption fixtures have evolved from simple negative pressure fixation to intelligent closed-loop compensation through the integrated development path of "sensing, controlling, and supporting. " Significant advancements have been achieved in deformation suppression, surface quality enhancement, and synergistic optimization of novel materials and structures. However, challenges remain regarding curved surface adaptability, sealing durability, and rapid switching between multiple varieties. Further system-level innovations in dynamic robustness, long-term stability, and deep integration of processes with equipment are required to transition this technology to practical production line applications.

5.2 Research prospects

To address the batch production demands of complex curved surfaces and difficult-to-machine materials in the aerospace industry, vacuum adsorption fixtures can achieve breakthroughs through a closed-loop system integrating "real-time sensing, digital twins, and adaptive support." This system could incorporate multimodal sensing, edge AI, and variable topology flow paths to enable millisecond-level vacuum field reconfiguration. Potential developments include high-temperature and abrasion-resistant flexible sealing materials, as well as rapidly reconfigurable modular structures, to overcome the key challenges of curved surface deformation, seal aging, and multi-species switching. Ultimately, this approach aims to establish a portable and scalable workshop-level digital twin fixture platform, enabling "zero-damage, high-precision, and widely applicable" machining of thin-walled components.

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