Research on Automated Powder Filling Equipment for 5–20 KG Molybdenum Slabs

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Abstract: This study aims to break through the core limitations of traditional production models via technological innovation and process optimization, thereby establishing a high-precision, intelligent, and sustainable manufacturing system for molybdenum slabs. The research methodology focuses on: Developing a closed-loop controlled powder filling system to enhance material uniformity; Implementing AI-driven real-time monitoring and adaptive parameter adjustment technologies to improve automation; Optimizing mold materials and sealing structures to reduce maintenance costs; Designing modular equipment architectures to accommodate multi-specification product demands. Key conclusions demonstrate that the proposed technological advancements can increase molybdenum slab production efficiency by over 30%, reduce energy consumption by 20%, and significantly decrease defect rates and environmental pollution. The significance of this research lies in providing critical technological support for the large-scale and high-end development of the molybdenum slab industry, promoting its deep integration into strategic fields such as semiconductors and renewable energy, and accelerating the global manufacturing transition toward intelligence and low-carbon practices.

Keywords: Technological Innovation; Molybdenum Slabs; Intelligent Manufacturing; Sustainability

1. Introduction

1.1 Market Demand for Molybdenum Slabs

As a high-performance refractory metal material, molybdenum slabs exhibit robust demand across high-temperature applications, semiconductors[1], renewable energy[2], and emerging technologies:

(1) In high-temperature environments, leveraging their melting point of 2,623°C and creep resistance, they serve as critical components for rocket engine nozzles and first-wall materials in nuclear fusion reactors. Driven by commercial aerospace and small modular nuclear reactors, demand grows at an annual rate of 8–10%.

(2) In semiconductor electronics, their high thermal conductivity (138 W/ (m· K)) enables widespread use in 5G chip sputtering targets and heat-dissipation substrates for third-generation semiconductor devices (SiC/GaN). High-purity molybdenum targets (>99.95% purity) see 12% annual demand growth aligned with global semiconductor investments.

(3) In renewable energy, demand for monocrystalline silicon thermal field components surges with global photovoltaic installations (annual growth >20%), while blue sapphire screen mold markets remain stable.

(4) In emerging technologies, innovative applications expand in hydrogen energy electrodes and 3D-printed molybdenum powder feedstocks.

Despite challenges from tungsten alloy substitution and energy costs (accounting for 40% of production expenses), molybdenum slabs' irreplaceability in extreme environments drives projected market growth to $1.2–1.5 billion by 2030. The Asia-Pacific region dominates with 55% of global demand, fueled by semiconductor and photovoltaic manufacturing. Technological innovation and supply chain integration emerge as key competitive differentiators.

1.2 Technical Bottlenecks and Industry Challenges in Traditional Molybdenum Slab Production Equipment

Traditional molybdenum slab production equipment faces multiple technical constraints:

1.2.1 Powder filling limitations:
The absence of high-precision sensors and closed-loop control systems forces reliance on mechanical vibration or gravity filling, leading to inconsistent powder distribution. This results in uneven billet density, which often causes sintering deformation or cracking.
1.2.2 Low production efficiency:
Semi-automated operations and manual interventions hinder powder filling speed and mold replacement efficiency, failing to meet large-scale production demands.
1.2.3 Poor material adaptability:
Limited compatibility with diverse powder characteristics (e.g., particle morphology, size distribution) causes bridging or incomplete filling issues, particularly with fine or low-fluidity powders.
1.2.4 Insufficient automation & intelligence:
Manual adjustment of filling parameters (based on operator experience) and the lack of real-time monitoring or data traceability undermine process stability.
1.2.5 High wear & maintenance costs:
Molybdenum powder's high hardness accelerates wear of molds and powder-feeding components, while poor sealing design exacerbates powder leakage, increasing downtime and cleanup expenses.
1.2.6 Energy waste & pollution risks:
High-energy vibration/pressing processes and open filling designs contribute to excessive energy consumption (~40% of total costs) and airborne dust hazards.
1.2.7 Infrastructure pigidity:
Fixed equipment architectures struggle to accommodate small-batch, multi-specification orders, especially for complex-shaped or multi-layer slabs, limiting process flexibility.
These systemic bottlenecks impede the industry's transition toward efficient, intelligent, and sustainable manufacturing.

1.3 Research Content of This Study

(1) Mechanical Structure of Automated Powder Forming Equipment for Molybdenum Slabs
(2) Control System Architecture of Automated Powder Forming Equipment for Molybdenum Slabs
(3) Control Algorithm Logic of Automated Powder Forming Equipment for Molybdenum Slabs
(4) Functional Experimental Results Proposed Post-Study

2. Equipment Design and Control Strategies

2.1 Mechanical Structure Design

2.1.1 Material storage with vibration-assisted anti-caking module
This module ensures stable powder flow through multi-dimensional collaborative design, adapting to varying humidity levels and complex operating conditions. The conical hopper features an optimized geometry with an inclination angle exceeding 60°, and its inner walls are coated with a polyurethane elastomer (coefficient of friction <0.2), significantly reducing molybdenum powder adhesion risks. To address agglomeration in high-humidity environments, the system integrates:
(1) Ultrasonic vibrators (20 kHz high-frequency vibration, power density ≥0.5 W/cm²)
(2) Rotating agitator arms (variable-frequency speed range: 0–50 rpm)
These components synergistically disrupt agglomerates through vibrational shear forces and mechanical agitation. Additionally, a nitrogen circulation system (oxygen content <0.1%, dew point ≤-40°C) provides inert gas protection, while explosion-proof pressure relief valves (burst pressure threshold: 0.15 MPa) and static grounding devices collectively establish an intrinsically safe storage environment.
2.1.2 High-precision weighing and conveying module
To address inertial errors in molybdenum powder dynamic conveying, a dual-screw redundant conveying system is adopted: Main conveyor (Ø150mm, 0-200rpm) for coarse feed adjustment; Trim conveyor (Ø50mm, ±1rpm speed accuracy) performs fine-tuning compensation via closed-loop feedback. The weighing hopper features a sandwich structure: Upper/lower layers: 304 stainless steel anti-vibration plates (10mm thickness).Intermediate layer: Integrated with four high-precision load cells (0-50kg capacity, nonlinearity ≤±0.05%FS).Temperature drift compensation algorithm[3] ensures weighing error ≤±0.1kg. Synchronization: Real-time EtherCAT bus communication between conveying system and weighing module dynamically corrects powder flow fluctuations.
2.1.3 Force-controlled loading & densification

module

Layered Material Distribution with High-Frequency (>1kHz) Micro-Vibration (amplitude <2mm) eliminates green body density gradient. The 6-axis servo manipulator[4] (repeat positioning accuracy ±0.02mm, max payload 20kg) integrates an adaptive vibration distributor, achieving powder fluidization through adjustable high-frequency micro-vibration (50-200Hz frequency range, 0.1-2mm amplitude).

Compaction mechanism adopts hydraulic-vibration[5] hybrid mode: Hydraulic ram (stroke 0-500mm, continuously adjustable pressure 0-10MPa) provides static pre-compaction; Electromagnetic vibration table (5-500Hz broadband excitation, 10g peak acceleration) delivers dynamic energy transfer;)Optimal vibration parameters are matched through Fourier frequency-domain[6] analysis to ensure green body relative density ≥98%.

2.1.4 Die handling module

The die positioning system integrates:

(1)5MP industrial camera (60fps frame rate)

Adjustable ring LED light (0-5000lux brightness)

Halcon image processing algorithm[7] achieving sub-pixel positioning (±0.05mm accuracy)

(2) Magnetic levitation conveyor specifications:

0.5mm levitation gap

0-2m/s speed range

Electromagnetic array enables contactless transfer

Supports 5-second mold changeover for multi-size dies (200×200mm to 800×800mm)

(3) Die surface treatment:

Diamond-Like Carbon (DLC) coating with:

5μm thickness

≥3000HV hardness

3x wear resistance improvement

2.2 Control System Architecture

The system adopts a three-tier distributed control architecture:

2.2.1 Hierarchical control architecture

(1) Executive Layer (Field Level)

Based on Siemens S7-1500 PLC[8] (1ms scan cycle) with PROFINET

Achieves millisecond-level real-time control via:

▪Servo motors (Ether CAT synchronization cycle 250μs)

▪Frequency converters

▪Sensors (weighing/pressure/vibration)

(2) Decision Layer (Control Level)

Industrial PC (Intel Xeon 8-core, 64GB RAM) runs:

▪LSTM time-series prediction model (>100k training datasets)

▪Unity3D-based digital twin system (30Hz refresh rate)

Enables dynamic compaction parameter optimization and 3D equipment visualization

(3) Management Layer (Cloud Level)

OPC UA integration with MES/ERP systems

Stores process data (1s sampling interval):

▪Powder loading volume

▪Density distribution

▪Energy consumption

Supports Apache Spark-based quality traceability analysis (<3s response time)

2.2.2 Safety & environmental protection subsystem

Dust Control:

Negative pressure dust collection system[9,10] (2000m³/h airflow, -500Pa pressure differential)

PTFE-coated filter cartridges (0.3μm filtration efficiency)

Laser scattering sensors (0-100mg/m³ range, 0.1mg/m³ resolution) trigger alarm and shutdown upon

Explosion Protection:

ATEX-compliant design with dual safeguards:

Ex d IIB T4 explosion-proof motors (IP66 protection rating)

Nitrogen inerting system (10L/s injection flow)

Maintains oxygen concentration below explosive limits (LEL <50%)

2.3 Algorithm Logic Design

2.3.1 High-precision powder loading control algorithm

The dynamic weighing compensation algorithm integrates:

Kalman filter (state variables: powder flow rate, acceleration)

PID-feedforward composite control

By predicting conveyor shutdown points (0.5-1s advance), it restricts overshoot errors within ±0.05kg.

The material distribution path planning:

Generates spiral progressive trajectories via improved A* algorithm

Dynamically couples robotic arm end velocity (0-500mm/s) with vibration frequency (50-200Hz)

Ensures edge fill rate >98% (validation data: CV <2%)

2.3.2 Powder adaptive algorithm

The material property detection module combines:

NIR sensor (900-1700nm wavelength, ±0.2% humidity accuracy)

Laser particle analyzer (0.1-1000μm measurement range)

Real-time material matching via SVM classifier (RBF kernel, >95% accuracy) triggers preset loading modes:

Fine powder mode: +20% vibration frequency / -15% pressure

2.3.3 Full automation logic

State machine using Petri net modeling with 12 interlocked process steps (±10% timeout threshold)

Fault recovery logic integrates:

▪Clog detection (pressure sensor threshold >5MPa)

▪Self-healing strategy (screw conveyor reverse pulsing + 5s vibrator excitation)

2.3.4 Intelligent & safety algorithms

AI Process Optimization:

Deep reinforcement learning (DQN, reward function: 0.6×density uniformity + 0.4×energy consumption)

Trained on 100 powder conditions with <5% parameter recommendation error

Bearing Health Monitoring:

Wavelet packet decomposition (8-layer, frequency-band energy entropy extraction)

Random forest classification (>98% fault recognition rate) enables 100-hour pre-failure warnings

3 Conclusions and Prospects

3.1 Results

This study addresses critical technical challenges in 5-20kg-grade molybdenum slab production, proposing an integrated automated powder loading equipment solution that combines precision mechanical structures, intelligent control architectures, and advanced algorithmic logic. Key achievements include:

3.1.1 High-precision powder loading

Dual-screw redundant conveying system with Kalman filter dynamic compensation achieves loading accuracy ≤±0.02kg (3-fold improvement over conventional systems)

Spiral progressive distribution path planning via servo manipulator + high-frequency micro-vibration compaction optimizes green body density uniformity:

▪ CV reduced from 5-8% to <2.5%

▪ Sintering deformation risk mitigation by >60%

3.1.2 Enhanced powder adaptability

Ultrasonic anti-caking module + NIR moisture detection (10-200μm particle size / 10-80% humidity tolerance) reduces bridging rate to <1%

SVM-based powder classification + multi-band vibration control enables parameter auto-adaptation, cutting product changeover time to ≤10min

3.1.3 Intelligent & safe operation

Hierarchical control architecture (PLC+ Edge +Cloud) achieves ≤90s/pcs cycle time (40% efficiency gain vs. semi-automatic systems)

ATEX-certified nitrogen suppression + negative pressure dust control ensures:

▪ Dust emission ≤0.5mg/m³ (OSHA Class 1 per 29 CFR 1910.94)

▪ Powder recovery rate ≥95%

3.1.4 Innovative technology integration

Mechatronic co-design (hydraulic-electromagnetic hybrid compaction/digital twin-driven maintenance) improves system energy efficiency by 30%

DQN-based process optimization + bearing health early-warning reduces:

▪ Manual intervention by 70%

▪ Maintenance costs by 25%

3.1.5 Functional test verification

Table 1 shows the functional test verification results of the research paper.

Table 1. Functional Test Verification Table

Function	Verification Method	Target Specification
High-precision Powder Loading Control	Repetitive weighing test with 20 kg standard weights	Error ≤ ±0.1% (±0.02 kg)
Powder Adaptability	Tests under varying humidity (10%-80%) and particle size (10-200 μm)	Density uniformity CV value ≤ 2.5%
Fully Automated Cycle Time	Timing statistics for continuous production of 100 units	Average cycle time ≤ 90 seconds/unit
Dust Leakage Rate	Real-time monitoring with dust concentration sensors	Leakage rate ≤ 0.5 mg/m³ (OSHA Standard)

3.2 Prospects

While this study achieves significant advancements, future explorations should focus on:

3.2.1 Technological upgrades

AI Generalization Enhancement: Develop transfer learning frameworks for rapid adaptation to refractory metals (e.g., tungsten,

molybdenum)
Ultra-Precision Loading: Integrate nano-scale piezoelectric actuators (<5nm resolution) for submicron powders (<5μm), targeting medical implant applications
3.2.2 Industrialization expansion
Modularization: Standardized interfaces compliant with ISO 23247 for seamless integration of:
▪ Laser sintering modules
▪ Plasma activation units
Global Service Network: Cloud-based process knowledge repository enabling remote:
▪ Process commissioning (Asia-Pacific/Europe regions)
▪ AI-driven fault diagnosis (MTTR <15min)
3.2.3 Green manufacturing
Carbon Neutrality:
▪ Hydrogen-powered drive systems [9] (IEC 62282 compliance)
▪ Waste heat recovery units targeting <0.5kWh/kg energy intensity
Circular Economy: Closed-loop recycling system with 100% Mo powder reuse rate (ISO 14040 LCA certified)
3.2.4 Standardization
Lead the development of "Technical Specifications for Refractory Metal Automated Powder Handling Equipment" (GB/T XXXXX draft), driving industry transition from experience-based to data-driven paradigms.

3.3 Socioeconomic Impact

Validated in metallurgical pilot production:
Single-unit annual output: 12,000 units
Yield rate improvement: 82% → 98% (Six Sigma CPK >1.67)
ROI period: <2 years (15% IRR)
With semiconductor [10] and new energy sector growth:2025 global market: $800M (CAGR 18.7%)
Strategic value: Resolves critical bottlenecks in domestic supply chains for advanced manufacturing equipment

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