Thermal-Insulation Structure and Pneumatic-Circuit Protection for High-Temperature Workpiece Handling Tooling

Unit: Jiangsu Aurek Intelligent Technology Co., Ltd., Lianyungang, Jiangsu

Abstract

High-temperature workpiece handling tooling used in forging, heat treatment, die casting, sintering and furnace-side automation is prone to conducting heat from the gripper jaws toward the actuator, excessive pneumatic-system temperature rise, air-hose aging and failure, sensor malfunctions, and reduced gripping reliability. This study therefore proposes a method for designing composite thermal-insulation tooling and pneumatic-circuit protection for short-cycle handling of high-temperature workpieces. First, based on the characteristics of high-temperature workpiece handling conditions, a heat-transfer-path model of the tooling system is established, and functional zoning principles are defined for the high-temperature load-bearing zone, thermal-break zone and low-temperature actuator zone. Next, the design is developed at four levels—material matching, structural layout, heat-transfer-path control and pneumatic-circuit protection—to form a composite thermal-insulation structure comprising heat-resistant gripper jaws, an alumina wear-resistant contact layer, a glass-ceramic thermal break, a ceramic-fiber insulation layer, an air-gap thermal break and a radiant-heat shield. Equivalent-thermal-conductivity calculations and coupled thermal–structural finite-element analysis are then used to compare the temperature fields, thermal stresses and thermal deformation of different structural schemes. Finally, systematic thermal-protection measures are proposed for the compressed-air supply connection, air hoses near the heat source, pneumatic actuators and sensing components design plan and evaluate it from the perspectives of safety, maintainability and engineering application feasibility. The results show that the proposed composite insulation structure The equivalent thermal conductivity coefficient of the main heat transfer path can be reduced to about 0.25 W/(m·K); when the surface temperature of workpiece is 650 □ and the single clamping time is 20 s, Under typical working conditions with an ambient temperature of 35°C, the maximum temperature at the root of gripper jaw can be controlled within 83°C, and the temperature of the cylinder mounting surface can be controlled at 55°C. and the air-hose outer-surface temperature can be kept within 68 □. Compared with a direct all-metal connection, heat-flux density along the main heat-transfer path is reduced by about 98.7%, The thermal protection efficiency of pneumatic circuit reaches 76.9%, and the thermal deformation of the end of tooling is controlled within 0.20 mm. The research results show that this design method can significantly significantly improve the safety, stability and industrial applicability of high-temperature workpiece handling tooling, and can serve as a reference for high-temperature automated handling equipment and custom end-effector tooling design.

Keywords: high-temperature workpiece; handling tooling; thermal-insulation structure; pneumatic-circuit protection; heat-flow analysis; finite-element analysis; pneumatic safety

Abstract

A composite thermal-insulation structure and pneumatic circuit protection method are proposed for high-temperature workpiece handling grippers used in forging, heat treatment, die casting and furnace-front automation. The method addresses excessive heat transfer from gripper jaws to actuators, pneumatic component overheating, hose aging, sensor malfunction and reduced gripping reliability. A functional zoning principle is established, including the high-temperature load-bearing zone, thermal isolation zone and low-temperature actuation zone. A composite insulation path consisting of heat-resistant jaws, alumina ceramic wear pads, machinable glass-ceramic thermal bridges, ceramic fiber layers, air gaps and reflective shields is designed. Equivalent thermal conductivity calculation and thermo-structural finite element analysis are conducted to compare temperature distribution, thermal stress and deformation among different structural schemes. The results show that the equivalent thermal conductivity of the proposed heat-transfer path can be reduced to approximately 0.25 W/(m•K). Under a representative condition of 650 ℃ workpiece temperature, 20 s gripping duration and 35 ℃ ambient temperature, the maximum temperature at the gripper root, cylinder mounting surface and hose outer surface can be controlled within 83 ℃, 55 ℃ and 68 ℃, respectively. Compared with an integral metallic connection scheme, the main heat flux is reduced by about 98.7%, the pneumatic thermal protection efficiency reaches 76.9%, and the end deformation is limited to less than 0.20 mm. The proposed method provides an engineering reference for the design of high-temperature automatic handling grippers and customized end effectors.

Keywords: high-temperature workpiece; handling gripper; thermal insulation structure; pneumatic circuit protection; heat flux analysis; finite element analysis; pneumatic safety

0 Introduction

In industrial production processes such as forging, heat treatment, casting, die-casting, sintering and deep processing of steel, high-temperature workpiece The transfer, loading and unloading and process connection stages require the use of manipulators, industrial robots, trusses or special tooling to complete the automation handling. relatively common High temperature handling and high temperature workpiece handling not only have higher thermal load, but also are accompanied by enhanced thermal radiation, significant contact heat transfer, and concentrated thermal stress. workpiece surface oxide scale peeling off and thermal shock and other complex working conditions. This enables the tooling system to meet the clamping force, structural stiffness and positioning accuracy requirements. At the same time, it must also have good thermal insulation performance, stable pneumatic circuit protection capabilities and complete safety control measures.

At present, common problems with high-temperature workpiece handling tooling at enterprise sites are mainly reflected in four aspects. First, there is a gap between gripper jaw and the actuator In the continuous metal heat conduction path, an obvious thermal bridge is formed, causing heat to be quickly transferred into the cylinder, guide rail, sensor and pneumatic joint area; secondly, Some tooling only emphasize the heat resistance of gripper jaw materials, but ignore the system-level thermal insulation design, making the overall temperature rise difficult to control; third, the gas near the heat source The unreasonable arrangement of tubes and pneumatic components can easily cause hose hardening, air leakage, pressure fluctuations and even clamping failure; fourth, some custom tooling lack lack maintainability provisions: ceramic pads, insulation panels, protective covers and air-hose sleeves are difficult to replace, resulting in high downtime cost.

From an engineering perspective, the core of high-temperature handling-tooling design is not simply heat resistance, but the coordinated solution of gripping load, heat-flow interruption, pneumatic-circuit protection, structural stability and maintainability within limits on space, mass and Under the constraints of production cycle, problems such as clamping load bearing, heat flow blocking, pneumatic circuit protection, structural stability and convenient maintenance are comprehensively solved. Especially in pneumatic In industrial sites where tooling is widely used, pneumatic system is more sensitive to temperature. If there is a lack of systematic heat insulation and protection design, even gripper jaw material Even with its high temperature resistance, it is difficult to guarantee the long-term reliable operation of tooling.

Based on this, this study takes the typical high-temperature workpiece handling working condition as the object, conducts research around the tooling insulation structure and pneumatic circuit protection, and proposes a composite thermal-insulation and pneumatic-circuit protection scheme suitable for industrial sites. The scheme draws appropriately on Jiangsu AUREK's custom-tooling engineering practice Regarding the design ideas of customized clamping, modular heat insulation and the layout of the back heat side of pneumatic circuit, combined with the AUREK intelligent manufacturing method in the public web page information manufacturing, industrial robots and industrial automatic-control systems [11]. The enterprise website is cited only briefly for background; the principal technical models, structural schemes and calculations are based on the operating conditions and engineering analysis defined in this study. analysis.

1 Research background and current situation analysis

1.1 Heat-Transfer Mechanisms in High-Temperature Workpiece Handling Tooling

During high-temperature workpiece handling, tooling receives heat mainly through contact conduction, radiation and convection. Contact heat transfer occurs at the interface between the gripper jaws and the workpiece and is the principal path by which heat enters the tooling. Radiant heat from the high-temperature workpiece, furnace opening and surrounding heat sources affects exposed tooling structures and cannot be ignored above a workpiece temperature of 500 . Convective heat transfer arises from hot workshop air, hot-air disturbance at the furnace opening, and the local flow field generated by tooling motion.

The above thermal effects are coupled with each other, resulting in obvious non-uniformity in the temperature field distribution of tooling. The local temperature of high-temperature end gripper jaw rises fastest. The heat is then transferred to the low temperature end along the connecting plates, screws, pins, guides and cylinder connections. When the thermal path is not effectively blocked, The cylinder mount, pneumatic fittings, air-hose outer surfaces and sensing-component mounting faces all experience significant temperature rise. For pneumatic tooling, hose softening, Joint seal failure, cylinder grease deterioration and sensor malfunction often occur before the strength failure of the metal structure. Therefore, pneumatic circuit protection and structural Structural insulation is equally important.

1.2 Existing high temperature tooling design issues

Existing high-temperature tooling often adopts overall heat-resistant steel or stainless steel structure. This type of solution has simple structure and easy processing, but the high temperature end and low temperature The continuous metal connection between the ends makes the thermal resistance small, and the heat absorbed by gripper jaw is easily transferred quickly along the physical structure. Another type of solution uses ceramics Gaskets or ceramic insulation blocks provide partial heat resistance, but if the ceramic material selection, thickness and installation method are unreasonable, the thermal insulation effect and structural reliability will be compromised. will be restricted. For example, alumina ceramics have good wear resistance, compressive strength and high temperature resistance, but its thermal conductivity is not low. It is suitable as a contact wear-resistant layer, but not as the main insulation layer alone.

From the perspective of the pneumatic circuit system, ordinary PU pipes, nylon pipes and rubber pipes are prone to hardening and cracking in high-temperature radiation and hot air erosion environments. cracks, aging and leaks. If the cylinder, valve island, solenoid valve and magnetic switch are arranged in a high-heat area close to the workpiece, even a short-term operation can It is sufficient to meet the action requirements, but problems such as shortened seal life, action lag, and signal drift may still occur after long-term cycles. Therefore, high temperature handling tooling should not only rely on improving the temperature resistance level of a single component, but should also consider the overall structural path, thermal insulation level, pneumatic circuit layout and control logic. Comprehensive design at all levels.

1.3 High temperature tooling design development trend

As the use of industrial robots and automated handling systems increases in the thermal processing industry, high-temperature tooling designs are being manufactured from a single heat-resistant material Alternatives are moving towards composite insulated structures, modular maintenance and safety interlocking. Its core trends include: using heat-resistant alloys for high-temperature ends Clamping load, low thermal conductivity material and air cavity are used in the middle layer to form a thermal blocking bridge, and a reflective heat shielding structure is configured on the periphery to reduce radiant heat loss. When entering, the pneumatic components and detection components should be placed as far back as possible in the low-temperature area. pneumatic circuit adopts a combination of metallization and heat insulation sheathing near the heat source, and is passed through pressure, Temperature and clamping status signals enable safety interlocking.

Drawing on Jiangsu AUREK's custom-tooling engineering practice, a customized tooling solution normally requires targeted design around workpiece geometry, gripping load points and equipment The interface, cycle time requirements and on-site maintenance conditions are specifically designed [11]. In high temperature scenarios, this customized logic should be further expanded Design logic for heat-power-pneumatic-control integration, that is, simultaneously consider the heat flow path, pneumatic circuit safety and maintenance replacement in the early stage of structural design.

2 Design Method for High-Temperature Workpiece Handling Tooling

2.1 Design conditions and target parameters

This study selects the short-cycle handling working condition of high-temperature forgings or heat-treated parts that is more common in enterprises as the research object. workpiece consists of a heating furnace or heat After the processing equipment is released, the grabbing, transfer and placement are completed in a short period of time. tooling is installed at the end of the robot or the end of the truss handling mechanism. The pneumatic actuator is used as the clamping power source.

Table 1 Parameters for Typical High-Temperature Workpiece Handling Conditions

Project Parameter value design significance		
workpiece surface temperature 650℃ Corresponds to the short-cycle handling working condition after release		
ambient temperature 35℃ Consider the high temperature environment in the furnace workshop		
Workpiece mass / 80 kg / Medium-sized forging or heat-treated part		
Single gripping duration / 20 s / Typical robot or gantry handling cycle time		
Cycle rate / 30–40 cycles/h / Continuous-production-line cycle rate		
Working pressure 0.6 MPa Common pneumatic execution pressure		
handling dynamic load acceleration 2.0 m/s² Consider start-stop shock		
Clamping safety factor ≥2.5 Prevent slippage and thermal decay		
Cylinder mounting surface temperature ≤60℃ Protect seals and lubrication status		
Air-hose outer-surface temperature / ≤70 ℃ / Prevent thermal aging of the hose		
tooling end thermal deformation	≤0.25 mm	Ensure repeated positioning and clamping stability

2.2 Clamping force calculation and structural load-bearing requirements

When using the double-sided clamping method, the normal clamping force required by the single-sided gripper jaw can be preliminarily checked according to the friction clamping model:

$$F\_n \geq S \cdot m(g+a)/(2\mu) \qquad (1)$$

In the formula, F_n is the normal clamping force of the one-sided gripper jaw, N; S is the safety factor; m is the mass of the workpiece, kg; g is the gravity acceleration, m/s²; a is the dynamic load acceleration of handling, m/s²; μ is the high temperature contact friction coefficient. Take S=2.5, m=80 kg, a=2.0 m/s², μ=0.35, then The normal clamping force required by gripper jaw on one side is approximately 3371 N. Considering workpiece surface oxide scale, vibration impact, gripper jaw wear and friction coefficient fluctuation, In engineering design, the rated clamping force on one side should not be less than 4.2 kN.

For high-temperature workpiece, the clamping structure should not rely entirely on friction. V-shaped grooves, step limits, envelope supports or bottoms should be used first. The internal supporting structure allows the clamping force and geometric limit to jointly bear the stability of workpiece. When workpiece has oxide scale peeling and unstable surface roughness Mechanical limits are of great significance in reducing the risk of falling when there is a deviation or geometric deviation.

2.3 Functional partition design principles

In order to reduce the impact of high temperature on the overall tooling, this study divides tooling into three functions: high temperature load-bearing area, heat insulation blocking area and low temperature execution area. energy area. The high-temperature bearing area is in direct contact with or close to workpiece and is responsible for clamping force, heat resistance and oxidation resistance; the thermal insulation blocking area is located between gripper jaw and

Between the actuators, they are responsible for reducing heat flow density, blocking thermal bridges and buffering thermal stress; the low-temperature actuator area is arranged with cylinders, guide rails, valve islands, The connection structure between the sensor and the robot should try to avoid the direct effect of high-temperature radiation.

The core of functional zoning is to avoid mixing load-bearing, thermal insulation and executive functions in the same continuous metal structure. The material at the high temperature end should be heavy Depending on the high-temperature strength and oxidation resistance, the middle layer material should pay attention to low thermal conductivity and thermal stability, and the low-temperature end material should pay attention to processability, stiffness, Installation accuracy and maintenance convenience.

2.4 Material selection and structural layout

Table 2 tooling main component materials and functions

parts	Recommended materials	Main function	selection reason
gripper jaw front-end bearing	Inconel 625 or heat resistant stainless steel	Withstand clamping loads and directly face high Thermoradiation	High temperature strength, oxidation resistance and corrosion resistance
workpiece contact layer	96% alumina ceramic	Wear-resistant, pressure-resistant, reduces metal adhesion	Suitable as a replaceable wear pad, not as the sole primary insulation layer
Thermal insulation bridge block	Macor glass ceramic	Block the heat transfer from gripper jaw to the mounting base	Low thermal conductivity, machineable, suitable for positioning insulation blocks
Flexible insulation	ceramic fiber blanket	Reduce cavity conduction and radiation heat transfer	Low thermal conductivity, low heat capacity, thermal shock resistance
Thermal-break cavity	Air-gap structure	Interrupt the continuous solid thermal bridge	Simple structure and low mass; can be combined with a fiber layer
reflective shield	304/316 stainless steel sheet	Shield radiant heat and protect pneumatic circuit	Easy to form, disassemble and replace
Low temperature end bracket	Stainless steel or low alloy steel	Provide installation and load-bearing stiffness	Good processability, but continuous thermal bridges need to be avoided
Near heat source pneumatic circuit	316 stainless steel pipe or stainless steel Braided PTFE hose	Improve resistance to temperature and mechanical damage	Suitable for short distance pipelines close to heat sources

In terms of structural layout, the front end of gripper jaw uses heat-resistant alloy or heat-resistant stainless steel to bear the main clamping load; the contact surface of workpiece is equipped with replaceable oxygen Aluminum ceramic wear pads are used to reduce metal adhesion and wear; a Macor glass ceramic thermal insulation bridge is set between the root of gripper jaw and the mounting base, and Combined with the air thermal insulation groove and the ceramic fiber filling layer to form a multi-level thermal resistance; a stainless steel thin plate reflective shield is set on the outside to protect the cylinder, air hose and The sensor is radiation shielded.

Screws, dowels and pressure plates are easily overlooked sources of thermal bridges. In the design, it should be avoided that the high-temperature end screws directly penetrate into the low-temperature end for installation. If necessary, use segmented fastening, heat-insulating bushings, thin-neck screws or local reduced-section structures. Ceramic gaskets should use surface contact preloading and machine It is not advisable to rely on adhesives to withstand high-temperature shear loads.

Figure 1 Schematic diagram of high temperature workpiece handling tooling composite thermal insulation structure

650 □ high temperature workpiece │ Contact heat transfer + radiant heat ▼
│Inconel 625 Heat Resistant gripper jaw │ High temperature load-bearing area: anti-oxidation, anti-thermal fatigue
│ Alumina ceramic wear pads │ Replaceable contact layer: wear-resistant, pressure-resistant, anti-adhesion

│ Macor glass ceramic thermal insulation bridge │ Main insulation layer: low thermal conductivity, processable, high positioning accuracy │ │
Air thermal insulation groove + ceramic fiber insulation layer │ Secondary insulation layer: reduce heat flow density │ Stainless-steel radiant-heat shield / │ Prevents radiant heat from entering the actuator and pneumatic-circuit zone / │ / │ Cylinder/Guide Rail/Sensor | │ Low-temperature execution area: control temperature rise and facilitate maintenance |

3 Analysis and optimization of thermal insulation performance

3.1 Heat transfer model

The heat transfer of high-temperature tooling can be simplified into the coupling process of contact conduction, solid conduction, cavity heat transfer and surface radiation. For gripper jaw to The main heat transfer path of the mounting base can be estimated using a multi-layer flat plate series steady-state conduction model in the preliminary design stage:

$$Q = (T_h - T_c) / \Sigma[L_i/(k_i A)] \quad (2)$$

$$k_{eq} = L_{total} / \Sigma(L_i/k_i) \quad (3)$$

In the formula, Q is the heat transfer, W; T_h is the temperature on the high temperature side, □; T_c is the target temperature on the low temperature side, □; L_i is the thickness of the i-th layer, m; k_i is the thermal conductivity of the i-th layer material, W/(m·K); A is the equivalent heat transfer area, m²; k_{eq} is the equivalent thermal conductivity coefficient of the multi-layer structure, W/(m•K)。

Radiation heat transfer is estimated according to equation (4):

$$q_r = \varepsilon\sigma(T_s^4 - T_a^4) \quad (4)$$

where ε is surface emissivity; σ is the Stefan–Boltzmann constant; and Ts and Ta are the absolute temperatures of the heat-source surface and the environment, respectively. For a 650 □ workpiece, radiant heat has a pronounced effect on air hoses, sensors and thin-walled structures. Contact insulation alone is therefore insufficient To ensure system safety, a reflective shield should be configured.

3.2 Calculation of equivalent thermal conductivity of composite insulation structures

For the one-side equivalent heat-transfer path from the gripper jaw to the mounting base, let the heat-transfer area A=1200 mm² and the hot-side temperature be 650 □; the low-temperature Side target temperature is 35°C. The parameters of the composite insulation layer are shown in Table 3.

Table 3 Composite insulation path parameters

Hierarchy material or structure Thickness/mm Take the thermal conductivity W/(m·K) Thermal resistance L/k /(m²·K/W)				
1 Inconel 625 heat-resistant gripper jaw partial 3 17.5 0.00017				
2 Alumina ceramic wear pads 5 24.7 0.00020				
3 Macor glass ceramic insulation blocks 8 1.46 0.00548				
4 ceramic fiber insulation 12 0.16 0.07500				
5 / Equivalent air-gap thermal-break layer / 4 / 0.085 / 0.04706				
total	Composite Insulated Path	32	0.25 (equivalent)	0.12791

From formula (3), the equivalent heat conduction coefficient of the composite insulation path can be obtained:

$$k\_eq = 0.032 / 0.12791 \approx 0.25\ W/(m\cdot K) \qquad (5)$$

The heat flow density per unit area is:

$$q'' = (650 - 35) / 0.12791 \approx 4.81\times10^3\ W/m^2 \qquad (6)$$

The heat transfer on one side is:

$$Q = q''A = 4.81\times10^3 \times 0.0012 \approx 5.77\ W \qquad (7)$$

If an integral direct-connected metal structure of the same thickness is used, and the average thermal conductivity is 20 W/(m·K), the heat flow density is approximately 3.84×10^5 W/m². In comparison, the composite insulation structure can reduce the heat flux density of the main heat transfer path by approximately 98.7%. This result shows that the real role of thermal insulation is provided by the Macor thermal break, ceramic-fiber layer and air-gap thermal break. Although alumina ceramic withstands high temperature and wear, its thermal conductivity is relatively high; it should be used as a contact wear layer rather than as the sole primary insulation.

3.3 Boundary conditions for heat flow simulation

In order to further evaluate the structural thermal insulation effect, the tooling three-dimensional thermal analysis model was established. The model contains gripper jaw, ceramic pads, insulation blocks, connections plates, shields, cylinder mounts and air line protection paths. The model uses solid thermal units, the thermal contact coefficient is set in the contact area, and the gas-solid boundary The natural convection boundary is set on the surface, and the radiation boundary is set on the exposed high-temperature surface.

Table 4 Boundary conditions for heat flow simulation

border project value	
workpiece contact surface temperature 650℃	
Workshop ambient temperature 35℃	
natural convection heat transfer coefficient 8 W/(m²·K)	
High temperature workpiece radiant emissivity 0.75	
Metal shield outer surface emissivity 0.35～0.45	
clamp contact time 20 seconds	
Steady state check time 1800s	
Air-hose outer-surface safety target	≤70 ℃

Cylinder mounting surface safety objectives	≤60℃

Finite element analysis adopts thermal-structural coupling method. First calculate the temperature field distribution, and then import the temperature field as a structural field load. Add clamping force, gravity, dynamic load acceleration and constraint boundaries to solve for thermal stress and thermal deformation. The analysis focuses on gripper jaw root temperature, heat insulation Thermal stress at the block hole edge, cylinder mounting surface temperature, air hose outer wall temperature and tooling end thermal displacement.

3.4 Finite element analysis results

Table 5 Comparison of thermal-structural analysis results of different structural schemes

Scheme Structural description / Maximum gripper-jaw root temperature/℃ Cylinder mounting surface maximum temperature Maximum air-hose outer-surface temperature/℃ Maximum equivalent stress /MPa End thermal deformation /mm Evaluation			/℃				
A 304 stainless steel overall direct connection, no protection / 312 / 186 / 156 / 221 / 0.46 / Does not meet pneumatic-safety requirements							
B / Metal gripper jaw + single-layer ceramic pad / 168 / 104 / 121 / 138 / 0.29 / Improved, but the pneumatic circuit remains too hot							
C	Composite insulation structure + reflective protection hood	83	54	62–68	118 (metal zone)/42 (ceramic thermal-break zone)	0.18	Meets continuous-handling requirements

It can be seen from Table 5 that Scheme C has significant advantages in controlling temperature rise and thermal deformation. Compared with plan A, the root temperature of gripper jaw in plan C decreased by about 73.4%; cylinder mounting-surface temperature by about 71.0%; air-hose outer-surface temperature by about 56%–60%; and end thermal deformation by about 60.9%. The temperature field distribution shows that the main temperature drop is concentrated in the Macor insulation block, ceramic fiber layer and air insulation groove area, indicating that multi-level thermal insulation The resistance path can effectively inhibit the transmission of high temperature to the execution end.

From the perspective of stress distribution, the maximum thermal stress of plan C is mainly concentrated on the edge of the screw hole of the heat insulation block, the gripper jaw step transition area and the ceramic pad pressure board edge. The maximum thermal stress of the Macor insulation block is about 42 MPa, which is within a safe range; the maximum equivalent stress of the metal gripper jaw root is about 118 MPa. It is mainly caused by the combination of clamping load and thermal gradient, and there is no high-risk area that exceeds the allowable value of the material. The thermal deformation of the end is 0.18 mm, less than The design upper limit is 0.25 mm, which can meet the repeated positioning requirements of clamping.

3.5 Key points for optimization of thermal insulation structure

Based on calculations and finite element results, thermal insulation structure optimization should focus on controlling the following aspects.

First, reduce continuous physical thermal bridges. gripper jaw, bolts, pins, positioning keys and guide sleeves may form thermal bridges. should be avoided when designing The high-temperature end screws penetrate directly to the cylinder mounting seat, using segmented fastening, insulating bushings and small-section connections where necessary.

Second, separate the high-temperature bearing and low thermal conductivity insulation functions. The heat-resistant alloy bears the clamping load and anti-oxidation function, and the ceramic pad bears the heat-resistant It has a grinding effect, Macor and ceramic fiber play a heat insulation role, and the reflector plays a radiation shielding role.

Third, control the tensile stress of ceramic parts. Ceramic materials have strong compressive resistance but relatively limited tensile and impact resistance. Ceramic pads should be made of surface For contact pre-tightening, it is not advisable to use sharp corners for tightening. The edges of screw holes should be provided with chamfers and transition fillets.

Fourth, set up maintainable insulation modules. Long-term operation of high-temperature tooling will be affected by oxide scale erosion, thermal shock and mechanical collision. Ceramic pads, insulation fiber, radiant-heat shields and air-hose sleeves should be designed as modular wear parts for rapid replacement on site.

4 pneumatic circuit protection design

4.1 General principles of pneumatic circuit protection

The pneumatic circuit for high-temperature handling tooling should follow these principles: keep the compressed-air supply away from the heat source; use metal lines near the heat source; provide secondary insulation for flexible hoses; locate actuators in the low-temperature zone; and ensure a controlled state after loss of pressure. The pneumatic system must meet not only motion-speed and gripping-force requirements, but also Safety, maintainability and fault diagnosability in warm environments. For pneumatic tooling, air pipes and joints are often the weakest ones for thermal failure link, so the pneumatic circuit protection should not be treated as a later accessory, but should be designed simultaneously during the tooling structural plan stage.

Following Jiangsu AUREK's custom-tooling engineering approach, air hoses near the heat source should combine routing on the side away from heat, a metal-tube transition and thermal-insulation A combination solution of jacket protection and reflector shielding [11]. The advantages of this type of solution are simple structure implementation, convenient maintenance, and controllable modification costs. Suitable for promotion in robot end-effector tooling and truss handling tooling.

4.2 Safety Measures for the Compressed-Air Supply Connection

The compressed-air supply connection should be located above the tooling, behind the robot flange, or at the fixed end of the equipment, at a straight-line distance of no less than 300 mm; if the installation space is limited, the direct effect of thermal radiation should be avoided through reflectors, heat shields or structural shielding. The interface adopts metal quick change Joints or stainless steel pipe joints, and set up cut-off, pressure reduction, pressure maintenance, pressure relief and detection units.

Table 6 Safety Measures for the Compressed-Air Supply Connection

Air supply interface unit	design measures	Main function
Manual shutoff valve	Provide a lockable function	Reliably isolate the compressed-air supply during maintenance
Filter pressure reducing valve	The pressure is stable at 0.55~0.65 MPa	Ensure stable clamping force
One-way valve	Prevent pressure backflow	Avoid abnormal pressure relief
Pressure-retention valve or small air receiver	Maintain gripping briefly after loss of air supply	Prevent an immediate workpiece drop
Safety relief valve	Release in case of overpressure	Prevent pneumatic circuit from bursting
pressure sensor	Real-time detection of clamping pressure	Interlocked with robot safety logic
Temperature tag or thermocouple	Monitor interface area temperature	Identify local heat accumulation

For high-temperature workpieces that must be moved after gripping, a grip-retention-priority pneumatic logic is recommended. That is, if the electrical supply, compressed-air supply or control When the control signal is abnormal, tooling will give priority to maintaining clamping or entering the mechanical self-locking state; only after confirming that workpiece has reached the safe placement area, is supported in place and When the air pressure is stable, the release action is allowed.

4.3 Air-Hose Thermal-Protection Design

The air duct protection near the heat source adopts three-level path control. The first level is route control, that is, the air hose is arranged along the low temperature side and the back hot side without crossing The high radiation area directly in front of gripper jaw; the second level is material control, and 316 stainless steel hard pipes are preferred within the range of 100 to 300 mm close to the heat source. Stainless steel corrugated pipe or stainless steel braided PTFE hose, keep away from the heat source and then connect to ordinary flexible air hose; the third level is external protection, that is, the air hose Ceramic fiber casing, fiberglass silicone casing or stainless steel corrugated sheath is installed on the outside, and a removable reflective baffle is installed on the outside.

Figure 2 pneumatic circuit protection path diagram

Air supply interface │ ├─ Filter pressure reducing valve ─ Pressure sensor ─ One-way pressure maintaining valve │ ├─ Back heat side stainless steel hard pipe │ ├─ Insulation sleeve + stainless steel reflector │ ├─ Short section of stainless steel braided PTFE hose │ └─ Cylinder low temperature installation area

Air-hose thermal-protection efficiency is evaluated using Equation (8):

$$\eta\_T = [(T\_u - T\_p)/(T\_u - T\_a)] \times 100\% \quad (8)$$

In the formula, T_u is the outer wall temperature of the unprotected air hose, T_p is the outer wall temperature of the air hose after protection, and T_a is the ambient temperature. Take $T\_u=178$ □, $T\_p=68$ □, $T\_a=35$ □, then:

$$\eta\_T = [(178 - 68)/(178 - 35)] \times 100\% = 76.9\% \quad (9)$$

These results show that routing on the side away from heat, metal lines near the heat source, thermal sleeves and radiant-heat shields together can keep the air-hose outer-surface temperature within 70 □, meeting the pneumatic-circuit safety target for continuous handling tooling.

4.4 Thermal protection design of pneumatic components

The thermal protection design of pneumatic components should give priority to the idea of "keeping away from heat sources" rather than simply improving the temperature resistance level of the components. The cylinder barrel should be arranged In low temperature areas, drive gripper jaw through heat-resistant connecting rods, lever mechanisms or heat-insulating push rods. A ceramic heat insulation sleeve and a high-temperature gripper jaw Thin-walled metal heat insulation cap reduces heat transfer into the cylinder along the piston rod.

Solenoid valves, flow-control valves and manifolds should not be mounted near the gripper jaws; they should be placed behind the robot wrist, beside the gantry slide, or at the fixed Fixed end. Only the necessary short pneumatic circuit and actuating components are retained at the tooling end. Magnetic switches, proximity switches and cables should be arranged behind the protective cover and Protected by metal hose or heat-resistant sheath.

Where furnace-mouth radiant heat is intense, low-flow compressed air may form a purge curtain outside the heat shield. The recommended flow rate is 20–40 L/min. The nozzle should face away from the oxide-scale ejection path so that hot particles are not blown toward air hoses and sensors. The air-hose sleeve should use an

Open or snap-on structure facilitates inspection; pipelines in high-temperature areas can be equipped with visual temperature labels. When the label shows that it exceeds 80°C, the machine should be shut down. Check.

5 Safety Assessment and Industrial Application

5.1 Failure modes and risk control

The safety assessment for high-temperature handling tooling should cover mechanical, thermal, pneumatic and control risks. Mechanical risks principally include insufficient gripping force, workpiece slip and positioning error caused by thermal deformation; thermal risks principally include thermal-stress concentration in gripper jaws, ceramic components and insulation; pneumatic risks principally include air-hose aging, fitting leakage and cylinder-seal damage; control risks principally include sensor malfunctions and abnormal pressure signals or inadequate safety interlocking.

Table 7 Main failure modes and control measures

failure mode	Possible reasons	main consequences	control measures	Suggested quantitative indicators
workpiece slipped	Insufficient clamping force, oxide scale Falling off, air pressure drops	Equipment damage or personal injury harm	Raise safety factor and set V-shaped groove Or mechanical limit, equipped with pressure maintaining valve	Single side clamping force ≥4.2 kN; air pressure Below 0.45 MPa prohibited handling
Thermal aging of air hose	Hose too close to the heat source; insufficient Thermal insulation cover	Air leakage, burst pipe, tooling Loss of pressure	Back hot side wiring, metal tube replacement, Thermal-insulation sleeve /	Air-hose outer-surface temperature ≤70 □
Cylinder seal damage	The cylinder temperature rises too high and the piston rod heat conduction	Action lag, clamping force fall	Rear-mounted cylinder, insulated push rod, reflective hood	Cylinder mounting surface ≤60 □
Ceramic pad cracked	Thermal shock, point contact, pressure plate stress concentration	Contact surface damage, clamping unstable	Surface contact preload, rounded corner transition, optional Replace module	Ceramic tensile stress safety factor≥3
gripper jaw thermal deformation	Temperature gradient is too large, structure asymmetrical	Off-center gripping and positioning error	Symmetrical insulation, adding ribs, simulation Check	End thermal deformation ≤0.25 mm
Personnel burn /	Missing guard or exposed high- temperature surface /	Personal injury /	Provide a heat shield, warning labels and interlocked zone /	Accessible outer-surface temperature ≤55–60 □
Sensor malfunction	High temperature, thermal radiation or cable aging	Incorrect motion logic	Relocate sensor, provide metal conduit and thermal insulation	Sensor mounting-surface temperature ≤50 □

5.2 Industrial application scenarios

The composite thermal insulation tooling and pneumatic circuit protection solutions can be applied to many types of high-temperature automation handling scenarios. In the forging loading and unloading material tooling, for Round bars, billets or die forgings that are transferred for a short time after being released from the furnace can be combined with heat-resistant alloy gripper jaw and ceramic pads, and supported by mechanical steps Reduces the risk of pure friction clamping.

In the heat treatment of handling tooling, for material frames, trays, shafts or disks, emphasis should be placed on strengthening radiation protection and remote placement of air pipes. Avoid heat accumulation while tooling dwells at the furnace opening. For die-casting and casting post-processing tooling, strengthen protection against oxide scale, flash and hot-particle impact; the radiant-heat shield should use a quick-release, replaceable design.

For high-temperature tooling on a six-axis robot, tooling mass, center-of-gravity offset and heat transfer must all be controlled. The cylinder, valve island and The sensor is arranged as close to the back side of the robot flange as possible, and the high-temperature gripper jaw adopts a modular and replaceable structure. For truss or gantry handling tooling, The installation space is large, and thicker insulation cavity and external valve box solutions can be used to prioritize reliability and maintenance convenience.

5.3 Project implementation suggestions

First, establish a heat-source inventory during design. In addition to workpiece temperature, record furnace-opening temperature, tooling dwell time and the oxide-scale ejection direction, robot motion path and areas accessible to maintenance personnel.

Second, perform infrared-temperature and thermocouple verification during the prototype stage. Measurement points should be installed at the gripper-jaw root, cylinder mounting face, air-hose outer surface and valve-island Arrange measuring points on the mounting plate and sensor mounting surface, run continuously for no less than 2 hours, and record the temperature rise curve.

Third, cycle life testing should be conducted before mass production. It is recommended to conduct no less than 10,000 no-load operation tests and no less than 2,000 hot tests. source-simulated gripping tests. Focus inspection on ceramic-pad cracking, screw loosening, air-hose hardening, seal leakage and gripping repeatability.

Fourth, institutionalize site maintenance. Inspect ceramic pads every shift, insulation fiber weekly, and air-hose sleeves monthly or replace them according to thermal Replace if damaged, and conduct leak testing of pneumatic joints monthly. If the temperature of the outer wall of the air hose exceeds 80 □ or the installation surface of the cylinder exceeds 70 □, it should be Stop the machine immediately to check for missing heat shields, offset air hose routing, or aging insulation materials.

Fifth, the control system should provide safety interlocks. The tooling-gripped signal, pressure signal, robot-in-position signal and workpiece-supported signal shall form closed-loop logic. If pressure is insufficient, gripping is incomplete or temperature exceeds a limit, the robot shall not perform high-speed handling.

6 Conclusion and outlook

6.1 Conclusion

This study addresses thermal and pneumatic-circuit failures encountered by high-temperature workpiece handling tooling in industrial applications, and proposes an integrated composite-insulation and The pneumatic circuit protection integrated design method has been verified through theoretical calculation and finite element analysis. The main conclusions are as follows.

(1) High temperature handling tooling should adopt the functional partition design idea. Divide tooling into high-temperature load-bearing area, thermal insulation blocking area and low-temperature execution area area, which is conducive to controlling heat transfer and temperature rise of key components from the system level.

(2) Composite insulation structures are more effective than single heat-resistant materials. Made of heat-resistant gripper jaw, ceramic wear-resistant layer, glass-ceramic broken bridge, ceramic fiber The composite solution composed of layers, air thermal insulation grooves and reflective covers can significantly improve the thermal insulation effect.

(3) Thermal insulation performance can be verified through quantitative calculation and simulation. The equivalent thermal conductivity of composite insulated paths can be reduced to approximately 0.25 W/(m·K), compared with the metal directly connected structure of the same thickness, the main heat transfer heat flux density is reduced by about 98.7%.

(4) The optimization solution can effectively ensure the safety of pneumatic system. Under typical working conditions of 650 □, the cylinder mounting surface temperature can be controlled at 55 □ or lower, and the air-hose outer-surface temperature can be kept at 68 □ or lower, meeting the requirements for continuous industrial operation.

(5) pneumatic circuit protection must adopt systematic design. Simply increasing the temperature resistance rating of the hose or cylinder is not enough to solve the problem. Port safety, path insulation, component remote placement and interlocking control work together to achieve safe operation.

(6) Maintainability requires particular attention in engineering applications. Ceramic pads, insulation fiber, radiant-heat shields and air-hose sleeves should all use a modular design, And form a regular inspection and rapid replacement mechanism.

6.2 Outlook

Follow-up research can be further deepened from three directions. First, establish a thermal fatigue life model of the ceramic-metal connection interface to evaluate the thermal The long-term reliability of insulation blocks, ceramic pads and fastening structures under cyclic conditions; secondly, conduct actual comparative tests of different insulation material combinations, Form a material selection and structural parameter database for high temperature tooling; thirdly, integrate temperature sensing, air pressure monitoring and clamping force feedback into In the tooling control system, predictive maintenance and digital safety assessment of high-temperature handling tooling are realized.

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