

# *Automated Welding Equipment in Construction Machinery Manufacturing*

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**Abstract:** Automated welding equipment has become crucial for improving production efficiency, ensuring weld quality, and reducing costs in construction machinery manufacturing. This paper outlines key equipment types and core principles, emphasizing advances in vision recognition, online inspection, and closed-loop parameter control. It describes automated welding processes and integrated implementation on assembly lines for large steel structures (e.g., main frames, chassis plates) and critical load-bearing components (e.g., booms, cylinder brackets), covering fixture design, path planning, parameter configuration, and MES integration. The paper discusses benefits—reduced welding time, stable weld quality, and minimized rework—and proposes flexible platform designs with multi-sensor fusion for real-time deviation compensation. A wheel loader case study demonstrates productivity gains, quality improvements, and positive ROI after automating main-frame and boom welding. Finally, in the context of Industry 4.0 and smart manufacturing, future trends include flexible welding cells, AI-driven adaptive process optimization via big data, and green, low-carbon welding technologies.

## **1. Introduction**

As the construction machinery industry expands and competition intensifies, manufacturers must meet demands for shorter lead times, consistent quality, and tighter cost control. Welding—essential for joining major components and structural parts—directly impacts performance, reliability, and safety. Traditional manual or semi-automatic welding suffers from inconsistent weld quality due to varying operator skills, physical fatigue, and slower speeds, leading to high defect and rework rates on complex or large workpieces. Automated welding equipment has therefore become crucial for boosting efficiency, ensuring consistent welds, and reducing costs. Recent advances in sensors, robot control, vision systems, flexible fixtures, and closed-loop process controls have evolved automated welding from basic semi-automatic machines into intelligent systems with integrated path planning, online inspection, and real-time compensation. For large structures (e.g., main frames, chassis plates) and critical load-bearing parts (e.g., booms, cylinder brackets), these systems precisely track complex weld paths and adapt parameters on the fly to minimize defects, enhance consistency, and improve mechanical performance. When linked with a Manufacturing Execution System (MES) and peripheral equipment, automated welding enables visualized, data-driven process management and full traceability from design through quality inspection. This paper

examines equipment types and principles, implementation workflows, key advantages and challenges, a comparative case study, and future prospects under Industry 4.0 and smart manufacturing[1].

## **2. Overview of Automated Welding Equipment**

### **2.1. Types of Automated Welding Equipment and Their Technical Principles**

Automated welding equipment replaces manual welding tasks with robotic arms, sensors, and intelligent control systems to achieve efficient, stable production. Structurally, such equipment can be divided into four categories: robot welding workstations, gantry-type welding units, collaborative robot (cobot) welding, and conveyorized automated welding systems. A robot welding workstation consists of a multi-axis industrial robot, a welding power source, and a wire-feed mechanism. The robot's articulated joints position the welding torch in three dimensions, making it well-suited for small to medium batches and diverse part types. Gantry-type welding units rely on a multi-axis gantry structure that can handle very large workpieces with high precision, and are commonly used for welding the main structural members of construction machinery. Cobot welding employs lightweight robotic arms with built-in safety features, allowing them to work flexibly in constrained spaces or in close collaboration with human workers; this approach is especially appropriate for welding and grinding complex subassemblies. Conveyorized automated welding systems integrate part feeding, positioning, and automated loading/unloading mechanisms to enable continuous batch welding of components, thereby greatly increasing production throughput[2].

From a technical standpoint, most automated welding equipment is based on arc welding or laser welding processes. Automatic wire feed, gas delivery, and a stable power source ensure a consistent weld pool. Typical systems use MIG/MAG (metal inert gas/metal active gas) welding technology, supplemented with current and voltage closed-loop control modules to maintain a stable arc. A weld-bead tracking system, often communicating with an MES or PLC via a fieldbus, provides data exchange with production management systems and allows remote monitoring. Teach pendants or offline programming software generate the robot's motion trajectories, which are then executed by the robot or gantry controller. Sensors play a critical role in weld tracking and quality monitoring: vision sensors or laser sensors capture weld-seam profiles in real time, and closed-loop control adjusts process parameters (current, voltage, torch orientation, etc.) dynamically to ensure weld consistency and mechanical performance. Modern systems may also store a library of preconfigured process parameters for different materials and weld geometries, enabling rapid changeover and repeatable weld quality. Flexible positioning fixtures with single-clamp setups minimize changeover time and boost equipment utilization. In addition, many systems feature online weld-defect inspection modules that detect flaws as welding progresses. Overall, these capabilities deliver high-precision, high-efficiency, and high-quality welding outcomes, making automated welding equipment a vital advancement in construction machinery manufacturing[3].

### **2.2. Current Development Status and Key Technology Advances**

In recent years, driven by the deepening implementation of smart manufacturing and Industry 4.0 initiatives, automated welding equipment has experienced rapid growth in the construction machinery sector. Leading equipment manufacturers worldwide have increased their investment in welding automation, introducing robot welding cells and laser welding solutions to boost both production throughput and quality control. Domestically, government policies promoting "intelligent manufacturing demonstration" and "robot substitution" have accelerated the adoption of robot welding on construction machinery production lines. The rise of locally produced robots and

critical components—with competitive cost and performance—has laid the groundwork for broader uptake of welding automation among small and medium-sized enterprises. Vision and sensor technologies represent key focal areas. Laser scanning and two-dimensional camera-based weld-seam recognition systems can adaptively locate complex seam profiles in real time, providing accurate data for weld tracking. Current and voltage sensor integration with closed-loop control has raised weld tracking accuracy to the millimeter level. Welding power sources and wire-feed mechanisms are evolving in a more digital and modular direction, adopting pulse-arc and dual-pulse control techniques to suppress spatter and stabilize the weld pool, which is essential for welding advanced materials like high-strength steel and aluminum alloys. Offline programming and simulation technologies have also made breakthroughs. Digital-twin-based virtual simulation platforms can verify weld process parameters and robot trajectories in advance, allowing fixture optimization and process validation before production begins—thus reducing commissioning time[4]. Innovations in flexible fixturing and quick-change interfaces enable rapid changeover between different workpieces, improving equipment utilization. The combination of collaborative robots and lightweight welding torches is shifting the industry toward “human-robot collaboration” models, opening up new possibilities for complex assembly and maintenance scenarios. Looking ahead, with the integration of artificial intelligence and big data technologies, as well as the promotion of multi-machine synchronized welding and cloud-based management platforms, the intelligence level of automated welding equipment will continue to rise. Deep-learning-based algorithms for automatic weld-defect identification and online compensation will play a pivotal role in enhancing weld consistency and stability. Green welding processes and energy-saving technologies will also become essential upgrades, supporting the sustainable development of the construction machinery manufacturing industry[5].

### **3. Application of Automated Welding in Construction Machinery Manufacturing**

#### **3.1. Automated Welding Processes for Structural Parts and Key Components**

Structural components in construction machinery often feature complex shapes and large dimensions, demanding extremely high welding precision and quality. Taking the main frame as an example, its welding areas involve multiple intersecting weld seams and transitions between horizontal and vertical surfaces. The automated welding process first requires exporting an accurate 3D model during the digital design phase and presetting welding parameters—such as current, voltage, welding speed, and wire-feed speed—based on the workpiece material properties (e.g., high-strength steel, low-alloy steel). Using offline programming software, one completes robot trajectory planning in a virtual environment and exports the teach program, ensuring that welding paths, collision detection, and fixture positioning are fully simulated and verified before actual production begins. In actual production, the structural parts are initially blanked by CNC cutting and formed by stamping to obtain individual subassemblies, which are then positioned in three dimensions on an automated welding platform. The platform is typically equipped with adjustable support fixtures that enable the workpiece to be clamped once at the designed orientation and allow for fine adjustments during welding as needed[6]. A multi-axis welding robot, carrying a specialized welding torch, works in concert with a vision sensor or laser-tracking system to scan the weld seam in real time and feed back position information. When the system detects that the weld seam deviates from its planned trajectory, it automatically adjusts torch orientation and welding speed through closed-loop control, ensuring that the weld seam remains aligned with the design path. This process not only improves weld quality but also significantly reduces defect rates caused by inconsistent manual operation.

Key components—such as booms and cylinder brackets—bear major structural loads and must

have uniform weld metallurgy and high fatigue strength. For these medium- to small-sized parts, collaborative robots (cobots) can be used for welding. Cobots offer excellent flexibility and can seamlessly switch between dedicated welding stations and areas where operators work alongside them. First, a dedicated welding fixture precisely clamps each part, and then the cobot, equipped with a lightweight welding torch, executes multi-layer, multi-pass welding according to the programmed procedure. Paired with an online weld inspection system, this setup monitors weld penetration depth and bead width in real time; if it detects any parameter anomalies, the system automatically issues an alarm and can interrupt the welding routine for manual inspection. Additionally, to minimize stress concentration in the weld, the welding procedure is designed with a reasonable sequence of passes and heat-control strategy between layers, reducing distortion and enhancing the overall mechanical performance of the component. In a real-world case, the above automated welding processes reduced the main-frame welding cycle for a wheel loader from over four hours of manual work to under two hours. Weld defect rates dropped by approximately 60%, while weld quality for boom components—judged by ultrasonic nondestructive testing—achieved a qualification rate of over 99%, and fatigue life improved by about 15% compared with manual welding. In summary, the automated welding processes for structural parts and key components—using digital design, precise robot trajectory control, online inspection, and flexible fixturing—achieve efficient, high-quality, and traceable production, providing reliable support for construction machinery manufacturing[7].

### 3.2. Integrated Automated Solutions for Whole-Machine Assembly Lines and Production Lines

In the production of complete construction machinery, welding is not merely an isolated process; it must coordinate smoothly with other stations on the assembly line to optimize manufacturing takt time and close the loop on quality control. A typical whole-machine assembly line consists of cutting, pre-assembly, welding, rough correction, fine correction, painting, and other stages. To seamlessly integrate automated welding into this flow, it is essential to focus on efficient part transfer between stations, positioning accuracy, and information-management integration. First, for part transfer, a flexible automated conveying system replaces traditional manual trolleys. By combining conveyor chains and rollers, the system can automatically sort and deliver workpieces of various dimensions and weights to the appropriate welding cells. To accommodate large components like main frames and chassis plates, transfer equipment between different welding cells is generally designed modularly; this approach not only supports handling of various part sizes but also shortens changeover time when switching between product types. Next, regarding cell layout, a four-stage “receive–weld–correct–release” arrangement is commonly adopted. Once a workpiece enters the welding station, a multi-axis positioning table ensures a one-time, precise fixture without the need for repeated manual adjustment[8]. After the welding cycle finishes, the workpiece is automatically pushed to a correction station where a hydraulic straightening unit quickly corrects welding-induced deformation; it then returns to the conveyor to proceed to the next process. This arrangement avoids repeated positioning errors and time loss from manual handling between stations. At the control-system level, welding robots are interfaced with the MES (Manufacturing Execution System) to enable the issuance of production orders, dynamic delivery of process parameters, and real-time collection of quality data. Based on the production schedule, the MES automatically assigns welding tasks to the relevant robots, sending each weld seam’s process parameters and trajectory information down to the robot controller to ensure consistent process execution when the workpiece enters production. During welding, the PLC (Programmable Logic Controller) and the robot controller communicate over a fieldbus; when the online inspection

system (e.g., laser scanning or vision camera) reports weld-seam deviations, the PLC immediately sends adjustment commands to the robot to enact closed-loop control. All quality and production data are then uploaded over the industrial Ethernet to the MES and ERP systems, providing a basis for subsequent production analysis and traceability. Additionally, to meet flexible demands for different machine models or small batch-variety production, a temporary welding station or mobile robot unit can be set up at the end of the production line. By using quick-change fixtures and offline programming capabilities, the welding cell can be rapidly redeployed to different sections of the line. This mode effectively reduces equipment idle time and enhances the production line's responsiveness and flexibility. In summary, by strategically planning conveyors, positioning platforms, and welding-cell layouts, and coordinating MES and PLC for control, automated welding equipment can tightly interlink with the whole-machine assembly line, markedly improving production efficiency and quality stability in construction machinery manufacturing[9].

## **4. Advantages and Challenges**

### **4.1. Production Efficiency and Weld Quality Improvements**

In traditional manual welding, production efficiency and weld quality fluctuate significantly because welders' skill levels vary, posture stability degrades as they fatigue, and individual performance speed changes. These factors make it difficult to meet construction machinery requirements for high consistency and high reliability. Once automated welding equipment is introduced, the most immediate benefit is a substantial reduction in per-piece welding time. For example, in a wheel loader's main-frame application, manual welding typically took over four hours, whereas a robot welding system—after offline programming and path optimization—reduced the same structure's welding time to under two hours, boosting production takt by about 50%. This efficiency gain not only lowers labor costs but also significantly increases workshop throughput, giving the manufacturer greater market responsiveness. At the same time, automated welding achieves highly stable weld quality by precisely controlling arc current and wire-feed speed in a closed-loop manner, combined with vision-based or laser-tracking real-time weld position monitoring. Data indicate that for critical load-bearing components (such as booms and cylinder brackets), the weld defect rate dropped by roughly 60% compared with manual welding; ultrasonic and X-ray NDT pass rates rose from 85% to over 99%[10]. Moreover, weld mechanical properties improved markedly: multi-layer, multi-pass automated welding ensures consistent penetration depth and uniform weld metallurgy, extending fatigue life by approximately 15% over hand welding. This improved consistency and reliability not only reduces subsequent rework and repair costs but also ensures a longer service life for machinery under demanding operational conditions. Furthermore, deep integration between the automated welding system and the MES enables data-driven, fully traceable production processes. Through the MES, process parameters are automatically loaded at each welding station, and real-time data are uploaded to the cloud; if any parameter anomalies or quality deviations occur, the system immediately raises an alarm and can trigger a stop-and-inspect procedure, effectively preventing batches of defective parts. This end-to-end visualization and control approach enhances both production efficiency and quality management, allowing the enterprise to deliver higher-quality construction machinery in shorter lead times.

### **4.2. Technical Challenges and Proposed Solutions**

In construction machinery manufacturing, automated welding faces challenges related to complex shapes and large sizes of welded parts. Large structural components (such as main frames and chassis plates) involve multiple intersecting weld passes, numerous bend angles, and confined



spaces, making precise, one-time positioning with traditional rigid fixtures difficult; this often leads to weld deviation and distortion. In addition, high-strength steel and alloy materials demand strict control of heat input and cooling rates; issues such as hot cracking and residual stress concentration make it hard to maintain stable weld quality. Thermal deformation and stress accumulation during welding also impose high costs and lengthy cycles in the correction stage. Moreover, weld-tracking and online inspection technologies can suffer from occlusion and glare when inspecting complex curved surfaces or deep recesses, degrading sensor accuracy and closed-loop control precision. Although offline programming and path planning improve programming efficiency, in actual production the workpiece's clamping error and fixture clearance can cause discrepancies between the real position and the planned trajectory, undermining weld consistency. Finally, integrating multiple pieces of equipment, multiple stations, and the MES introduces challenges in communication delay and coordinated control; if welding parameters can't be delivered promptly or inspection data aren't fed back in real time, batch quality fluctuations may occur.

To address these challenges, one can adopt a flexible welding platform with adjustable positioning modules, using modular fixture components and automatic adjustment mechanisms to achieve rapid, accurate single-setup placement of various workpiece specifications, thus reducing manual correction time. Vision-based and laser-scanning weld-tracking techniques—by deploying multiple sensors at different angles and using optical filtering algorithms—can provide stable recognition on complex curved surfaces. Combined with laser-profile tracking to dynamically capture the weld-seam centerline, these approaches raise weld-tracking accuracy to the millimeter level. To mitigate hot-cracking and distortion in high-strength plates, preheating of the plates before welding and the use of pulse-arc or multi-stage control techniques can regulate heat input, reducing stress concentration from excessive penetration. Within a multi-pass welding process, applying a rational welding sequence and interpass heat-control strategy can further minimize overall thermal distortion. By leveraging digital twins and offline simulation platforms, one can pre-validate welding parameters, fixture layouts, and robot paths in a virtual environment—predicting deformation trends to optimize the process and shorten commissioning cycles. For integration challenges, utilizing industrial Ethernet-based real-time communication protocols ensures data synchronization among PLCs, robot controllers, and the MES; edge-computing nodes can preprocess sensor data to reduce cloud-latency, achieving faster response for welding parameters and quality data. Multi-sensor fusion technology can also combine visual, laser, and current/voltage sensor information to build a multi-dimensional model of weld status, providing early warning of anomalies and enabling adaptive compensation. In summary, through flexible fixturing, intelligent sensing, optimized heat-input strategies, digital simulation, and multi-system collaboration, the technical bottlenecks of automated welding in construction machinery manufacturing can be effectively overcome, boosting weld quality and production efficiency.

## **5. Typical Case Analysis**

### **5.1. Implementation Case of Automated Welding in a Construction Machinery Enterprise**

A large wheel-loader manufacturer introduced a gantry-type automated welding system to improve both main-frame weld quality and production capacity. During the project's initiation phase, the company and its equipment supplier collaborated to match the main-frame's 3D model to the welding process, identifying critical weld positions and determining the fixture configuration. In the offline-programming environment, digital simulations were repeatedly run to verify the robot's welding trajectories, weld-sequence planning, and process parameters—ensuring proper seam coverage and heat-input control. Once production commenced, each workpiece was delivered by a flexible conveyor system to the positioning station, where a multi-axis fixture clamped the main

frame precisely in its design orientation on a single setup. A gantry-type welding robot equipped with a multi-sensor weld-tracking system scanned the seam profile in real time. If any deviation remained within  $\pm 0.5$  mm, the system automatically adjusted torch angle and wire-feed speed via closed-loop control; if the offset exceeded this threshold, the system issued an alarm and transferred the part for manual inspection. After implementing these solutions, the main-frame welding cycle time dropped from four hours of manual welding to under two hours with automation, boosting monthly output by roughly 40 percent. Simultaneously, weld-defect rates fell from 8 percent before automation to 1 percent, significantly reducing rework costs.

## 5.2. Quality Assessment and Benefit Analysis for Key Components

For automated welding of key load-bearing parts (such as booms), the enterprise used a collaborative robot paired with optical sensors to perform multi-layer, multi-pass welds. Before and after automation, the company conducted ultrasonic and X-ray nondestructive testing to compare weld geometry and metallurgical structure between robotic and manual welds. Results showed that weld penetration was consistent and fusion surfaces were complete in the automated parts, with virtually no slag inclusion or lack-of-fusion defects. The microscopic grain structure in the weld metal also appeared finer, and fatigue-life tests on the weld regions indicated about a 15 percent increase in service life over manual welds. From an economic standpoint, the equipment's payback period was approximately 18 months. Over one year, the automated system saved about ¥2 million in welder labor costs and roughly ¥800,000 in rework and quality-failure expenses; after accounting for maintenance and energy-use costs, the net financial gain was substantial. Following this success, the company extended the same automated-welding approach to chassis panels and rear-axle housings, realizing economies of scale and maximizing overall benefits. This case clearly demonstrates that automated welding not only enhances the quality stability of critical components but also delivers considerable economic returns for the enterprise.

## 6. Conclusion

Automated welding equipment can significantly boost production efficiency and weld quality in construction machinery manufacturing. Through digital design and offline programming, robots or gantry-type welding systems can execute complex weld paths with high precision—halving the welding cycle time for large structural parts (such as main frames) and reducing weld-defect rates to below 1 percent. For critical components like booms and cylinder brackets, collaborative robots combined with multi-sensor online inspection ensure consistent weld penetration and uniform microstructure, improving fatigue life by approximately 15 percent. Deep integration with the MES enables automatic delivery of process parameters and real-time traceability of quality data, effectively reducing rework costs and increasing line utilization. Looking ahead, driven by Industry 4.0 and smart manufacturing, automated welding will evolve toward greater flexibility and intelligence. Multi-sensor fusion and deep-learning algorithms will enable higher-precision online compensation on complex curved seams. Digital-twin and virtual-simulation platforms will shorten commissioning cycles and accelerate the introduction of new product models. Wider deployment of collaborative robots and lightweight welding torches will give production lines enhanced responsiveness to varied part mixes. Furthermore, green, low-carbon welding techniques and energy-efficient processes will become industry standards, providing strong support for sustainable development in construction machinery manufacturing.

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