



Process of Restoration of the Sliding and Rotary Frame of the Rear Boom of Backhoe Loaders JCB, CAT, Volvo, Terex, Deer, New Holland and Analogues

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Abstract

Against the backdrop of increasing pressure on the operating profitability of heavy equipment fleets, driven by supply chain volatility and the high costs of unplanned repairs, the presented methodological guideline summarizes the interdisciplinary foundations of restoring critical components made of high-strength cast iron — sliding and swing frames of backhoe loaders. An integrated methodological platform is formed for diagnostics, restoration, and quality control, combining economic-engineering analysis of total cost of ownership (TCO), metallurgical approaches to controlling the heat-affected zone (HAZ), and techniques of on-site precision machining. Within the scope of the work, it is demonstrated that the described approach, based on a strict regulation of thermal cycling of welding operations using nickel alloys and on the use of mobile boring and build-up welding systems, makes it possible not only to radically reduce downtime and current expenses compared to replacement, but also to provide the restored component with wear resistance that exceeds the original specifications. At the same time, implementation limitations are documented: the need for capital-intensive equipment and increased qualification requirements for technical personnel. It is argued that the institutionalization of an engineering-centric culture of asset restoration is a strategic imperative for strengthening operational resilience and for an actively managed life cycle of equipment. The materials presented in this work will be of interest to service engineers, heads of technical departments, repair specialists, and technical directors of enterprises in the construction and mining industries.

Keywords: Remanufacturing, Backhoe Loader, High-Strength Cast Iron, Total Cost of Ownership (TCO), Heat-Affected Zone (HAZ), Welding with Nickel Alloys, Mobile Line Boring, Non-Destructive Testing (NDT), Wear Resistance, Asset Life Cycle Management.

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INTRODUCTION

The global construction equipment market maintains a steadily ascending trajectory, driven by large-scale infrastructure investments and ongoing urbanization, especially in economies that are undergoing intensive development. As of 2024, the aggregate value of the backhoe loader segment ranges from 5.9 to 22.4 billion USD, with an expected compound annual growth rate (CAGR) from 2.6% to 6.7% over the next ten years. In this logic, a backhoe loader is not merely a unit of the fleet, but a high-yield production asset whose operational readiness directly determines project margins. However, high utilization intensity exposes a systemic industry risk: significant financial losses due to unplanned downtime of critically loaded assemblies [1, 2].

According to industry analytics for 2024, unplanned downtime annually costs the 500 largest global companies nearly 1.4 trillion USD, which corresponds to 11% of their combined revenue; in heavy industry, the cost of one hour of downtime may reach 59 million USD [2-4]. Against this background, the failure of such a complex and highly loaded component as a swing frame made of high-strength cast iron poses a nontrivial challenge to maintenance services, namely restoration or replacement. The canonical solution, ordering an original OEM part, is associated not only with high cost, but also with unacceptable delivery times measured in weeks, which multiplies losses. The alternative in the form of purchasing used or remanufactured components on the secondary market reduces initial expenditures, but carries substantial risks of latent defects and reduced service life.

As a result, a paradox emerges: standard strategies are either economically disadvantageous over the lifecycle horizon or technologically unreliable. Industry guidelines and technical literature typically limit themselves to general regulations for welding cast iron without metallurgically controlled management of the heat-affected zone (HAZ), or they describe individual operations, such as machining, in a fragmented manner and outside the context of an integrated restoration technology. This leads to a persistent methodological

vacuum: there is no unified, comprehensive methodology integrating three critically important components — economic justification based on total cost of ownership (TCO), metallurgical control employing scientifically valid welding technologies that prevent martensitic embrittlement and cracking of cast iron, and engineering precision ensured by modern on-site precision machining technologies to restore factory tolerances.

The aim of the methodological guide is to systematize the interdisciplinary foundations of the restoration process for swing and sliding frames and to propose an integrated, stepwise conceptual model for their defectoscopy, restoration, and quality control.

The scientific novelty lies in the formalization of a holistic engineering paradigm that synergistically unites economic analysis, applied materials science, and precision machining technologies, whereby what was initially an improvised repair process is transformed into a reproducible and controlled technological process.

The author's hypothesis proceeds from the assumption that the systematic application of the methodology presented not only restores the functionality of a worn assembly, but can also enhance its operational characteristics (in particular, wear resistance) compared to the original part, while simultaneously ensuring optimal total cost of ownership indicators and minimizing downtime. This approach appears to be the most realistic path toward increasing operational resilience and efficiency in heavy equipment fleet management.

CHAPTER 1. OPERATIONAL AND FINANCIAL SIGNIFICANCE OF BACKHOE LOADER UPTIME

This chapter develops an economic rationale in favor of implementing advanced restoration technologies. The approach is fundamentally broader than the trivial cost comparison repair vs. replacement and represents an integrated assessment of asset management, operational risk, and life-cycle cost.

Market Dynamics and The Central Role of the Backhoe Loader as an Asset

A backhoe loader is not merely a vehicle in the equipment fleet but a highly liquid production asset that generates revenue in construction, agriculture, and municipal services. Its multifunctional architecture, which combines a front loader and an excavator, ensures irreplaceability across a wide range of operations: from building construction and road works to routine tasks in emerging markets [1]. The scale of its economic significance is confirmed by global market dynamics: in 2024 the market volume was estimated at 5.9 billion USD, with a projected increase to 6.9 billion USD by 2030 at a compound annual growth rate of 2.6% [1]. At the same time, a number of analytical sources indicate a steeper trajectory: from 22.39 billion USD in 2024 to 37.33 billion USD by 2032 at a CAGR of 6.6% [2].

The key determinant of demand expansion is the accelerated deployment of infrastructure investments, primarily in developing economies [1]. Government programs aimed at supporting economic growth are reallocating significant budget resources to infrastructure projects and thereby reinforcing demand for versatile earthmoving and loading equipment, including backhoe loaders [1]. The year 2023 is illustrative: in the global construction sector more than 4700 infrastructure initiatives were launched, which significantly increased demand for high-performance earthmoving machinery [3]. Under these conditions, failure and downtime of a critical component — for example, the swing frame — are immediately translated into lost revenue and schedule disruption. Consequently, maintaining maximum operational availability of the backhoe loader fleet is not merely a task of technical maintenance but a strategic economic imperative.

In-Depth Analysis of Total Cost of Ownership (TCO) for Heavy Machinery

Total cost of ownership (TCO) is a fundamental integral indicator that assesses the true cumulative cost of a capital acquisition over its entire life cycle [5]. The TCO approach includes not only the initial purchase price, but also all subsequent costs associated with operation, maintenance, repairs, as well as final disposal or replacement of the asset [5]. Deep understanding and controllability of these variables make it possible to reduce total costs, extend equipment service life, and make more substantiated decisions regarding its replacement [6].

Total cost of ownership (TCO) includes two mutually complementary categories of costs — fixed (ownership) and variable (operation) — and functions as an integral indicator of economic efficiency throughout the entire life cycle of a machine [7]. Such structuring gives analytical transparency to calculations, allowing direct linkage of budgetary decisions to the factors that shape cost both over time and under changing utilization intensity.

Fixed costs (ownership) do not depend on the actual utilization level of the equipment and define the baseline financial contour of the asset. They include: acquisition costs, covering purchase price, transportation, commissioning, attachments, and financial expenses (loan interest) [8]; depreciation as the systematic reduction of value due to physical wear and market fluctuations [7]; insurance, taxes, and fees, typically calculated as a share of book value (approximately 2–5% per year) [7]; storage and infrastructure — provision of secure and safe placement of the machinery, which for a single fleet unit may require on the order of 6,000–12,000 USD annually [7].

Variable operating costs scale with the intensity of use and reflect the actual operating mode of the fleet. Key line items include: fuel and process fluids — one of the dominant positions; for example, a mid-size backhoe loader can consume significant volumes of diesel fuel, generating daily expenditures measured in hundreds of USD [7]; maintenance and repair — scheduled preventive operations (oil and filter changes) and unscheduled restorative work, which in aggregate reach, by estimates, 15–20% of the initial cost per year [8]; operator costs — wage expenses for qualified personnel including taxes and social contributions [7].

In the logic of TCO, maintenance and repair costs should be interpreted not as a passive budgetary burden, but as manageable investments in extending service life and reducing total ownership costs over a long horizon. High-quality restoration of critically loaded assemblies (for example, the swing frame) increases reliability, reduces future operating expenses, and prevents cascading failures that are substantially more expensive, thereby improving the TCO profile of the asset [7, 8].

Quantitative Assessment of the Financial Impact of Unplanned Downtime

Unplanned downtime in heavy equipment fleet management is not a line stoppage, but a systemic risk that grows into a cascade of consequences: from lost output and penalties for schedule slippage to capacity reallocation, overtime, logistics overload, and reputational damage in the contracting market [8]. In practice, a single failure triggers a chain of secondary effects: adjacent units stand idle, work in progress accumulates, the project critical path extends, injury risk increases due to rushed recovery efforts, and the cost price of works spreads upward against the backdrop of night shifts and urgent deliveries.

Current industry estimates confirm that this is a macro-level risk: the 500 largest companies in the world lose on unplanned downtime on the order of 1.4 trillion USD annually, which is equivalent to approximately 11% of their annual revenue [9]. In heavy industry, a single hour of downtime can cost up to 59 million USD, and this upper bound is approximately 60% higher than the 2019 level [10]. At the same time, based

on the 2024 cross-section, average values are approximately 25 thousand USD per hour, with growth to more than 500 thousand USD for large operators [12].

Against this backdrop, the downtime paradox emerges: incident frequency, thanks to preventive measures and improved maintenance procedures, is not increasing and often is decreasing, but the cost of each specific incident is rising due to inflation, extended spare parts lead times, and higher labor costs [12], [13]. In other words, rare but expensive failures consume the lion's share of the savings from improved maintenance.

The total cost of unplanned downtime is most convenient to decompose into several layers (Total Cost of Downtime, TCoD):

Direct production losses: foregone marginal profit and/or penalties for underdelivery [8], [12].

Contractual sanctions and urgency premiums: penalties for missing key milestones, surcharge on contractor services in emergency mode [8], [12].

Production and logistics costs: express delivery, overtime, rental of substitute machinery, unplanned shutdowns of adjacent systems.

Reputational and commercial consequences: reduced reliability scoring with customers, loss of options for future volumes, increased insurance cost [8].

For planning, it is convenient to use a simple estimate of expected annual losses:

$$E[\text{TCoD}] = \lambda \cdot (\text{MTTR} \cdot \text{Ch} + \text{Cpenalties} + \text{Clogistics} + \text{Cquality}) \quad (1)$$

where λ is the failure intensity (incidents/year), MTTR is the mean time to recovery, Ch is the cost of one hour of downtime (within the range [12], taking into account the tail from [10] for specific segments), and the remaining terms are associated effects [8, 12, 13]. Even with λ close to zero, a high Ch makes the risk materially significant.

Even a short stoppage can replicate itself across the operations network: under high capacity utilization, every lost minute at a bottleneck multiplicatively increases total project duration (bottleneck and critical path effect). Hence the nonlinear growth of costs and the breach of schedule KPIs. If an hour costs 25–50 thousand USD [12], then a 20-hour delay is 0.5–1.0 million USD in lost output alone; at the upper end of the range the figures are even more aggressive [10]. In reality, this is further compounded by express logistics, overtime, price erosion due to batch resizing, etc. [13].

The articulation joint (articulated frame section) is a node with high stress concentration and cyclic loads. Typical failure mechanisms: fatigue cracking in the heat-affected zone, bushing and pin wear with misalignment, fretting corrosion, local overloads. Risk management assumes:

– Early defect detection: regulated nondestructive testing (visual/dimensional inspection, dye penetrant/magnetic particle/ultrasonic testing), monitoring of vibro/acoustic anomalies, clearance and coaxiality control.

– Proper repair engineering: validated recovery procedures (WPS/PQR), heat input control, post-processing and finishing, in-place line boring, restoration of fits, final geometry.

– Quality assurance: 100% nondestructive testing after repair, dimensional report on geometry, registration of the part's genealogy (as-repaired).

Even a short downtime due to a crack in the articulation joint that required, say, one full day for nondestructive inspection, preparation, and weld/machining work, generates costs that far exceed the cost of the repair itself at Ch from the [12] range; and in certain segments such costs reach millions within a matter of hours [10].

Building in-house competencies in high-quality recovery of critical nodes is not a question of whether we will do it cheaper than the OEM, but rather management of mean time to recovery (MTTR) and, therefore, the dominant component of TCoD.

Assume that thanks to in-house repair competency, MTTR is reduced from 72 to 24 hours (a savings of 48 h). At Ch = 50,000 USD/h (the middle of the [12] range) the direct savings on a single incident will be:

$$48 \times 50,000 = 2,400,000 \text{ USD,}$$

excluding penalties, logistics, and secondary effects [8], [12], [13]. Even if the actual Ch is lower (25 thousand USD/h), the savings, and therefore the captured value, are still 1.2 million USD — an amount sufficient to pay back a training program, shop tooling, and quality procedures within the horizon of one or two incidents. For segments with the upper estimates of hourly cost [10], the benefit profile is even higher.

Operational advantages.

– Reduction of dependency on supply chains (bottlenecks, parts shortages, variability in lead times) — the key cost driver of incidents in 2024 [13].

– Quality control and repeatability: proprietary WPS/PQR, measurement protocols, digital repair history.

– Inventory economics: ability to restore instead of storing expensive large-format spares.

– Safety and compliance: in-house nondestructive testing control and compliance with internal standards when working with load-bearing elements.

For systemic downtime risk management, it makes sense to introduce a mandatory control set:

– Reliability and maintainability: MTBF/MTTR for key nodes, failure intensity λ , defect-type distribution.

- Time economics: hourly downtime cost Ch by site/shift/type of work [12], with separate logging of extreme scenarios [10].
- Logistics: mean and 90th percentile lead times for critical components (the driver of incident cost growth in 2024 [13]).
- Repair quality: share of repeat failures after recovery, nondestructive testing protocols, geometric maps.
- Commercial: penalties/bonuses under contracts, impact on execution of the project critical path [8, 12].

In conditions where incident frequency is not increasing, but the cost of each downtime event has risen sharply due to inflation, logistics delays, and expensive labor [12, 13], the maximum effect comes from reducing MTTR. For nodes of the articulation joint class this is achieved through creating and institutionalizing in-house competencies in high-quality recovery: validated technologies, nondestructive testing, dimensional assurance, and a controlled supply chain. Given the hourly downtime cost ranges recorded in 2024 [9, 10, 12], this is not a technical option, but an economically justified program to reduce the total cost of risk.

Repair Versus Replacement Decision: Cost-Benefit Analysis Based on Data

When a slewing frame fails, the head of the technical service department faces a choice: procurement of a new original (OEM) component, purchase of a used or remanufactured unit on the secondary market, or execution of an in-house major overhaul. A justified decision is not limited to comparing initial prices; it requires a multifactor assessment that includes total cost of ownership, downtime risks, predictability of lead times, and reliability of the final result.

Supply of a new OEM component provides certified quality, guaranteed compatibility, and manufacturer support. However, this option is associated with the highest initial expenditures and, which is critically important for operations, with high schedule uncertainty: official dealers are often unable to commit to a completion date, since it depends on warehouse stock levels and logistics [14]. Delays of days and even weeks are typical, especially for rare modifications; each day of downtime is converted into substantial losses, as previously demonstrated by calculations [15].

The secondary market (used and remanufactured assemblies) is attractive due to reduced price. For example, a slewing frame for a JCB 3CX may cost about 2,623 USD, and for a Caterpillar 428D approximately 950 EUR (\approx 1,113 USD) [17, 18]. However, the savings are counterbalanced by technological and operational uncertainties: unknown load history, incomplete warranty support, probability of latent defects (including fatigue microcracks), and reduced remaining service life [15]. At the same time, the market

for remanufactured products in general demonstrates growth, primarily in low-income regions, where such units are 30–40 % cheaper than new ones [3]; consequently, the economic effect is realistic, but requires mature procedures for incoming inspection and risk management.

In-house major repair implies initial investments in tooling and personnel training; however, in the medium and long term it provides an optimal balance of cost, timing, and quality control. Expenditures on consumables (welding wire, electrodes, bushings at 17–75 USD) are incommensurably lower than the price of a new part [19]. The key advantage is full control over the process and the schedule: restoration can be completed within several days, minimizing downtime losses. Additionally, the application of modern build-up welding and line boring technologies makes it possible to form wear-resistant surfaces with a service life comparable to or exceeding the original assembly, subject to strict compliance with regulations on geometry and thermal influence.

Development of internal restoration competencies is not only a means of cost reduction, but also a mechanism for increasing operational resilience. Under conditions of the market simultaneously moving toward increasingly complex and expensive new machines, and toward more affordable but less predictable remanufactured products, the ability to perform high-quality restoration in-house closes the strategic gap [3]. This reduces dependence on volatile supply chains and maintains high fleet readiness. Accordingly, investment in equipment — for example, in a mobile line boring and build-up welding unit costing several thousand dollars — should be interpreted as insurance against multi-thousand-dollar losses due to downtime [11, 21].

Thus, the selection of the preferred alternative must be based on comparison of:

- the total cost of ownership including downtime losses and schedule uncertainty;
- the defect risk profile and the expected remaining service life;
- the requirements for traceability and warranty support;
- the availability of qualification and technological tooling.

For rare modifications with long lead times and high downtime cost, given competent personnel, in-house restoration is rational; for critically loaded assemblies in warranty-sensitive applications, OEM supply is justified; acquisition on the secondary market is acceptable only under strict incoming diagnostics, documented service history, and acceptable return conditions. This approach ensures a scientifically justified, economically and technologically validated management practice.

To formalize the decision-making process, the following comparative analysis Table 1 is proposed.

Table 1. Comparative cost-benefit analysis: Frame replacement versus in-house restoration (compiled by the author based on [16, 17]).

Indicator	New OEM part	Used or refurbished part	In-house restoration
Initial costs (USD)	High (thousands)	Medium (\$1,000 - \$3,000)	Low (cost of consumables)
Lead time (days)	5 - 20+ (depending on availability)	3 - 10 (search and delivery)	2 - 4
Associated downtime costs	Very high	High	Minimal
Warranty period (months)	12 - 24	0 - 6	Internal quality assurance
Expected service life (engine hours)	100% of nominal	40% - 70% of nominal	100% - 120% of nominal (with strengthening)
Total life cycle cost	Very high	Medium/High	Low
Cost per 1000 engine hours	High	Medium	Very low

The conducted analysis convincingly demonstrates that, despite capital-intensive initial investments in equipment and personnel training, in-house restoration ensures the minimum total life cycle cost and the highest operational readiness, remaining the defining factor of competitiveness.

CHAPTER 2. UNDERSTANDING THE COMPONENT: MATERIALS SCIENCE AND FAILURE MODES

This chapter examines the materials science aspects of the component itself, forming the technical foundation for subsequent repair methodologies. Without an understanding of its material nature and failure mechanisms, it is impossible to ensure successful restoration.

Metallurgical Profile of OEM Swing Frames: Ductile and Gray Cast Iron

Swing and slide frames of backhoe loaders are made of cast iron, an iron-carbon alloy with a mass fraction of carbon generally above 2%, which fundamentally distinguishes it from steel and defines the specifics of repair and restoration technologies [24].

Two types of cast material are most widespread in heavy-duty assemblies. Gray cast iron is characterized by a graphite phase in the form of plates (flakes). Such morphology results in high machinability, pronounced vibration damping properties, and significant compressive strength. At the same time, flake graphite forms sharp stress concentrators, as a result of which the material exhibits low fracture toughness under tension and typically fails in a brittle manner, without noticeable plastic deformation [24].

High-strength cast iron with spheroidal graphite (spheroidal iron formed by magnesium modification) differs by crystallization of graphite in the form of spheroids. The absence of sharp stress concentrators typical of flake morphology provides this material with substantially higher ductility, impact toughness, and tensile strength compared to gray cast iron [24]. For this reason, for highly loaded and critical parts, including swing frames, leading manufacturers (JCB, CAT, Volvo, etc.) prefer high-strength spheroidal cast iron.

To further enhance performance characteristics, cast iron is alloyed. The main additional elements are chromium, nickel, and molybdenum, which increase hardness, strength and, critically, resistance to abrasive wear and impact loads [20, 27]. Chromium promotes the formation of hard carbide phases, sharply increasing abrasive wear resistance, whereas nickel and molybdenum ensure an increase in overall strength and impact toughness of the material [27]. It is precisely this complex, multicomponent microstructure that dictates strict requirements for welding procedures: an improperly selected thermal cycle can irreversibly destroy the target balance of properties.

Failure Classification: Diagnostics of Wear, Fatigue Cracking, and Brittle Fracture

Understanding the physics and kinetics of damage is the starting prerequisite for correct defect assessment and scientifically justified selection of repair actions in pin-jointed assemblies of the boom-stick-hydraulic cylinder type. In real operation, degradation is reduced to three dominant mechanisms that differ in tribological nature, rate of damage accumulation, and risk profile for load-bearing capacity: abrasive-adhesive wear, fatigue cracking, and brittle fracture. Correct identification of the prevailing mechanism must invariably precede any restorative work, because it determines the repair technology and the required inspection depth.

Abrasive-adhesive wear develops at small amplitudes of relative displacements and high contact pressures, when friction occurs in boundary or mixed lubrication regimes (the Stribeck curve region). Adhesive galling and the formation of microparticles convert the contact into a three-body abrasion mode: particles that enter the clearance drastically intensify the abrasive component. At the macro level one records an increase in radial clearance, ovality, enlargement of hole diameters for pins and bushings, and local scoring and scuffing of mating surfaces. Contamination (sand, dust, corrosion products), defects or destruction of seals, and extended relubrication intervals accelerate the breakdown of protective boundary films and increase wear

intensity. Misalignment and skew of the holes (edge loading, accelerated ovality “cut-out”), unfavorable material pairing in the friction couple (for example, a soft bushing without solid lubricant additives against a hardened pin resulting in accelerated adhesion and galling), and lubricant starvation under high dust load aggravate the process significantly. Practical diagnostics relies on measuring diameters and ovality using bore gauges of class 0/1, roughness control (for bushings after finishing typically $R_a \approx 0.8\text{--}1.6 \mu\text{m}$ with refinement per technical specifications), analysis of wear products in the lubricant, and assessment of the condition of dust boots and seals; based on the results, a wear map is compiled with reference to the direction of working loads.

Fatigue cracking arises under repeatedly varying loads of alternating amplitude and sign, which are characteristic of digging cycles and lever-kinematic bending. Crack initiation occurs in stress concentration zones — at hole edges, at sharp section transitions, in heat-affected zones, and at weld toe notches — followed by stable growth governed by cyclic fracture laws in region II of the $da/dN\text{--}\Delta K$ diagram. The long subcritical stage makes the mechanism “hidden”: even when cracks are still small, the stiffness of the joint is already reduced, the safety margin is being consumed, and vibration sensitivity increases. Evaluation of accumulated damage must take into account the actual, non-uniform load spectrum with overloads and block loading; use of Miner’s rule is permissible only with corrections for crack growth retardation after overloads. Surface condition of the holes (scoring, dents, undercuts after improper weld build-up or line boring) and geometric inaccuracies (misalignment, ellipticity, jaw non-parallelism) strongly affect the process by increasing the eccentricity of load application and bending components in the pin. To detect and map defects, magnetic particle testing (MT) is used on ferromagnetic steels, penetrant testing (PT) along edges and transitions, ultrasonic testing (UT) for subsurface cracks, and visual-measurement inspection with endoscopy of hard-to-access areas.

Brittle fracture is a sudden loss of load-bearing capacity without pronounced preceding plastic deformation. It occurs either under a single overload exceeding the ultimate strength, or under accelerated unstable growth of a previously formed fatigue crack. The risk increases at reduced temperatures (shift of the ductile-to-brittle transition), high loading rates, presence of sharp notches, and unfavorable structural and metallurgical factors (for example, graphite inclusions and coarse carbides that facilitate crack propagation). Considering the higher tendency of cast iron toward brittle behavior compared to steel, this risk is subject to systematic assessment and control at all stages of operation and repair ([26]).

The choice of repair strategy must be rigidly correlated with

the established failure mechanism. When wear dominates, the priority is to restore geometry, load-bearing contact area, and a functional tribological pair. Effective methods include build-up welding with controlled heat input followed by machining — line boring, reaming, honing — to nominal dimensions and required roughness while ensuring coaxiality (including in-field line boring with bar systems). For steels, low-hydrogen electrodes and wires are used; parameters are assigned with consideration of the carbon equivalent $CE = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$ and the requirements of EN 1011-2, under strict control of interpass temperature and thermal pauses to avoid temper embrittlement and distortion. For minor wear, installation of repair bushings (bronze, steel with hard coating, polymer composites with PTFE/bronze) to match the nominal pin is permissible; for significant wear, oversize bushings together with an increased-diameter pin are used, with careful verification of seal effectiveness. Hardened-and-tempered pins with induction-hardened journals are recommended; for severe abrasion, hard chrome plating or HVOF coatings are applied. For bushings, bronze or bimetallic solutions with antifriction layers are preferred; the required roughness is selected to ensure lubricant retention and minimal run-in wear. Lubricants are NLGI-2 class greases with EP additives and molybdenum disulfide; the lubrication regime is intensive purging until contaminated grease is displaced, with simultaneous restoration of dust boots and seals and regular contamination monitoring (by cleanliness code with target levels agreed with the OEM).

When fatigue cracks are detected, the goal of repair is complete elimination of crack initiation sites, prevention of crack re-initiation, and recovery of the designed stiffness. The crack is removed down to sound metal with mandatory PT/MT verification; stop drilling is permissible only as a temporary measure for emergency operation and does not resolve the repair requirement. Weld joint configuration is assigned with smooth transitions (elimination of undercuts), selection of filler materials by strength and impact toughness, and the use of low-hydrogen processes (for example, E7018 or GMAW with controlled diffusible hydrogen). For high-strength steels, preheating and regulated interpass temperature according to CE are required; if necessary, local tempering or heat treatment is performed to reduce residual stresses. Geometric correction includes ensuring coaxiality of holes by in-assembly line boring, restoring jaw parallelism, removing sharp edges, and rationalizing fillet radii in stress concentrator zones. Final inspection includes MT/UT of welded joints, measurement of residual deformations, and, where access is available, bench static and cyclic testing of the assembly. Ignoring cracks and limiting work to superficial cosmetic restoration leads to accelerated defect growth and a sharp increase in the probability of catastrophic failure within a short time.

When a pronounced risk of brittle fracture is present, especially for cast iron components, the task is to eliminate the scenario of sudden loss of load-bearing capacity. Metallurgically correct approaches for gray cast iron include the use of nickel electrodes or wires or brazing, controlled preheating and slow cooling to reduce thermal stresses and prevent hot cracking; rigid fixtures that create shrinkage stresses should be avoided. Essential measures include the removal of notches (grinding sharp edges, forming smooth fillets, weld build-up transitions without undercuts) and operational constraints: avoiding low-temperature impact loading modes, observing rated lifting capacities and hydraulic pressures, and timely replacement of worn pins and bushings to prevent local overloads.

Reliability improvement is ensured by strict quality control at all stages. Metrological and geometric control includes a measurement map of diameters, ovality, and coaxiality before and after repair, referenced from clean surfaces and recorded in a protocol. Nondestructive testing combines VT with PT/MT along edges and UT on massive elements, with repeated verification after weld build-up and machining. Sealing assemblies are subject to restoration with inspection of seal grooves and monitoring of breathing; early grease leakage serves as an indicator of lost tightness. Lubricant selection and service intervals are adjusted for actual dust loading and duty cycles; for severe conditions, purging old grease via increased greasing frequency is justified. Material pairings are reasonably formed according to the scheme hard pin — softer bushing to create a controlled wear path; under extreme abrasion, induction hardening of the pin and hard coatings (chrome, carbide HVOF coatings) are applied. Documentation and traceability are critical: material grades, welding and heat treatment regimes, consumables used, and NDT results form the basis for repeatable reliability and subsequent failure analysis.

In generalized form, the failure mechanism must dictate the repair technology: with dominant wear, geometric and tribological restoration (weld build-up, bushing installation, line boring with proper lubrication and sealing); with fatigue, complete crack removal with engineering-correct welded restoration, residual stress management, and geometry control; with a threat of brittle behavior, especially in cast iron components, priority is given to metallurgically correct processes and, if necessary, replacement of the assembly ([26]). Ignoring the true nature of damage and applying cosmetic interventions systematically accelerates degradation and increases the probability of catastrophic failure.

Primary Inspection and Non-Destructive Testing (NDT) Protocols

Before any decision regarding restoration is made, the frame must undergo comprehensive diagnostics to ensure

accurate qualification of the scale and nature of the damage. The diagnostic protocol includes the following mandatory stages:

Complete cleaning: The frame must be completely freed from contaminants, oil, lubricants, and old coatings by means of high-pressure washing, steam treatment, and mechanical removal. Such preparation is critical for high-quality visual inspection and proper execution of NDT.

Visual testing (VT): A detailed inspection of the entire surface is carried out, with targeted attention to areas around holes, weld seams, and mounting points. The objective is to identify visible cracks, deformations, corrosion sites, and atypical wear patterns.

Dimensional analysis: Using calipers, bore gauges, and micrometers, the diameters of all pin bores are measured in multiple mutually perpendicular planes. This allows quantitative assessment of wear and ovality and comparison of the results with the nominal values specified in the manufacturer's service documentation.

Liquid penetrant testing (PT) or magnetic particle testing (MT): Mandatory non-destructive testing methods for detecting surface and near-surface defects inaccessible to the unaided eye. **Liquid penetrant testing (PT):** A penetrant fluid is applied to the cleaned surface, which, due to capillary forces, fills all surface discontinuities. After removal of excess penetrant, a developer is applied, which draws it out of the defects and forms a clear high-contrast indication trace [28]. **Magnetic particle testing (MT):** The method is applicable exclusively to ferromagnetic materials, including cast iron. The part is magnetized, and a suspension with fine ferromagnetic particles is applied to the inspection area. In the region of cracks, the magnetic field is distorted, forming leakage fields that attract the particles and produce a visible ridge above the defect.

Determination of acceptable/not acceptable status: Based on the totality of the obtained data, a final decision is made using clear measurable criteria. The frame is deemed not restorable in the presence of through-thickness cracks in load-bearing elements, significant plastic deformation (bending), or unacceptable wall thinning caused by corrosion. In all other cases (bore wear, local noncritical cracks), the frame is considered a candidate for restoration.

At this stage, the foundation for successful repair is established. Ignoring or performing NDT only formally leads to the risk of missing hidden defects. Restoration of such a unit is not only economically unjustified but also extremely dangerous, as it may result in sudden failure under load.

CHAPTER 3. ADVANCED WELDING METHODOLOGIES FOR HIGH-STRENGTH CAST IRON REPAIR

This section is the methodological core of the guide, where

strictly regulated step-by-step protocols are systematized, derived from the metallurgical principles formulated in Chapter 2.

Metallurgical Imperative: Control of the Heat-Affected Zone (HAZ) to Prevent Martensitic Embrittlement

The quality of cast iron welding is determined by 90% by the depth of understanding and the degree of controllability of processes in the heat-affected zone (HAZ). The HAZ is the region of the base metal that does not melt, but undergoes microstructural changes under the action of the welding arc heat [29]. It is precisely here that the main cause of failure in cast iron component restoration is concealed.

The elevated carbon content in cast iron leads to the fact that, under rapid heating and subsequent sharp cooling typical of arc welding, transformations occur in the HAZ that are identical to the steel quenching process [31]. Carbon dissolved in austenite at high temperatures does not have time to precipitate in the form of graphite and results in the formation of an extremely hard but brittle martensitic structure, as well as brittle iron carbides [25]. This state is described as martensitic embrittlement.

In immediate proximity to the ductile and tough weld metal, a thin quenched layer of the base metal with sharply pronounced brittleness arises. Shrinkage stresses accompanying weld cooling are concentrated precisely in this zone and almost inevitably initiate cold cracks, either immediately after welding or under the first service loads [29].

From this follows the main technological imperative: the entire procedure of cast iron welding must be aimed at preventing the formation of martensite in the HAZ. This is achieved by controlling the thermal cycle, primarily by reducing the cooling rate. Every subsequent step considered in the guide — preheating, interpass temperature control, slow cooling, the use of reduced currents and special welding materials — is a direct instrument for regulating the cooling rate and, consequently, the microstructure in the HAZ.

Table 2. Recommended parameters for temperature control for malleable cast iron (compiled by the author based on [33, 36, 37]).

Section thickness (mm)	Recommended minimum preheating temperature (°C)	Maximum interpass temperature (°C)	Recommended cooling method
< 25	120 - 150	250	Covering with thermal insulation mats
25 - 50	200 - 250	350	Covering with thermal insulation mats or burying in sand
> 50	250 - 400	450	Slow cooling together with the furnace or burying in sand

Strict adherence to this three-link protocol transfers welding from the category of simple metal deposition to the mode of

Temperature Regime Control: Preheating Protocol, Interpass Temperature Control, and Slow Post-Weld Cooling

Temperature regime control is a cornerstone factor in the effectiveness of cast iron repair. This is not a recommended practice but a strictly regulated technological procedure consisting of three interrelated stages.

Preheating: Its key objective is to equalize the temperature field between the weld zone and the bulk of the component [33]. This reduces thermal stresses and, critically, slows the cooling of the weld metal and the heat-affected zone after arc extinction [34]. Slower cooling provides additional time for carbon diffusion and prevents the formation of brittle martensite.

Temperature: The preheating level is determined by section thickness, the grade of cast iron, and the selected welding process. As a general guideline, for components thicker than 25 mm, the minimally reasonable range is 120–250 °C [33]; for larger and structurally more complex castings, the temperature may be increased.

Methods: Preheating is performed using gas burners, induction heaters, or a furnace. When using burners, heating must be slow and uniform, covering an extended area around the repair zone in order to avoid local overheating [36].

Interpass temperature control: In multipass buildup welding, it is not permissible for the component temperature to fall below the established preheating level. This maintains the stability of metallurgical transformations and prevents the formation of brittle structures in previously deposited layers.

Slow post-weld cooling: This stage is equivalent in importance to preheating. Immediately upon completion of welding, the component must be isolated from the environment to ensure maximally slow and uniform cooling. The most effective approach is to cover the repaired area with thermal insulation blankets (asbestos or ceramic) [37]; as an alternative, the area may be buried in dry sand or vermiculite [33]. Cooling is continued until room temperature is reached; forced cooling with water or compressed air is strictly prohibited (Table 2).

controlled heat treatment, which ensures the formation of a high-quality and reliable joint.

Selection of Welding Materials: A Comparative Guide

Understanding the role of filler material in cast iron welding is a fundamental condition for obtaining a reliable and long-lasting joint. The key task is to make the correct choice between nickel-based and iron-based materials, since their properties influence the structure and service performance of the weld in different ways.

Nickel alloys (ENi-CI, ENiFe-CI). These materials are traditionally considered the most preferable for arc welding of cast iron. Their value is determined by the low solubility of carbon in nickel: even under significant dilution with a high-carbon base metal, brittle carbide phases do not form. As a result, the weld metal retains ductility, resistance to cracking, and good machinability [38].

— AWS ENi-CI (pure nickel, about 99% Ni). This filler material is particularly effective for the repair of gray cast irons, where it is critical to ensure easy subsequent machining, including thread cutting. It forms a relatively soft weld with limited strength, which makes it optimal for single-pass joints and buttering operations [40].

— AWS ENiFe-CI (nickel-iron alloy: ~55% Ni, ~45% Fe). A versatile electrode used both for repair of malleable and high-strength cast irons and for joining cast iron to steel. The weld metal is characterized by increased strength, ductility, and resistance to crack formation, as well as reduced sensitivity to

harmful impurities (phosphorus, sulfur). Unlike pure nickel, this alloy produces a stronger joint that remains machinable with cutting tools [38].

Iron-based materials (cast iron rods, steel electrodes).

— Cast iron rods. Used primarily in gas welding. Their application requires mandatory high preheating (up to 600–650 °C), but they offer the best ability to reproduce the color and structure of the original cast iron [38]. Their use in arc welding is limited due to process complexity.

— Steel electrodes (for example, Washington Alloy EST). They are cost-effective, but their functional capabilities are extremely limited. The weld is characterized by high rigidity and significant shrinkage stresses, and it cannot be machined. Therefore, they are applicable only in non-critical cases where machinability and residual stress reduction are not essential [40].

Specialized overlay materials. During the restoration of working surfaces of holes subjected to intensive wear, hardfacing alloys are used. The most common are high-chromium cast iron-based materials and cobalt alloys (satellites). They produce a coating with high hardness and wear resistance, exceeding the characteristics of the base metal [41].

Table 3 presents the selection matrix for welding materials for cast iron repair.

Table 3. Matrix for selecting welding materials for cast iron repair (compiled by the author based on [38 – 42]).

Material type	Key properties	Primary application
ENiFe-CI (Nickel-Iron)	High strength, ductility, good machinability, crack resistance	Structural repair of malleable and high-strength cast iron, welding of thick sections, joining cast iron to steel.
ENi-CI (Pure Nickel)	Maximum machinability, soft weld	Repair of casting defects, buildup of the first (oil) layer, repair of thin-walled parts.
High-chromium alloy	Very high hardness and abrasive wear resistance	Final buildup of working surfaces of holes to improve wear resistance.
Cast iron rod (gas welding)	Ideal match in color and structure	Restoration work, repair in stationary workshop conditions with furnaces.
Steel electrode	Low cost, non-machinable weld	Only for noncritical, nonstructural repairs.

Based on the above, when performing structural repair of the swing frames of backhoe loaders, the only technically justified choice is electrodes of the nickel-iron system ENiFe-CI.

Step-By-Step Welding Procedure

This procedure integrates the provisions set out above into a single regulated technological cycle that requires strict adherence.

Defect preparation: All cracks and areas of degraded metal are subject to complete removal. Mechanical grinding with abrasive tools or air-carbon arc gouging is used. After gouging, the surface is additionally cleaned with a grinder

to remove the carburized and hardened layer [39]. The edge contour is formed smoothly, without sharp transitions or burrs.

Preheating: Performed strictly according to the protocol specified in section 3.2. The temperature regime is controlled with a contact thermometer or a pyrometer at several points surrounding the repair area.

Application of the oil layer: The entire prepared cavity is covered with a single overlay layer using a small-diameter (2.5 or 3.2 mm) pure nickel (ENi-CI) electrode. The resulting ductile nickel buffer isolates subsequent fill passes from the high-carbon base material and thereby reduces the tendency of the heat-affected zone to crack [35, 39].

Execution of fill passes: Filling is performed using nickel-iron electrodes (ENiFe-CI). Welding is carried out at the minimally stable current recommended by the manufacturer in order to limit heat input. A short bead (stitch) technique with bead lengths not exceeding 30–50 mm [28] is used, with their placement staggered (wandering sequence) to distribute heat evenly and reduce distortion. The arc is directed at the weld pool rather than the base metal to minimize its penetration and mixing [33].

Peening: Immediately after each short bead, while the metal remains ductile (red-orange heat), light frequent peening is performed using a rounded peen of a pneumatic or manual hammer. Such treatment forms compressive residual stresses that compensate for shrinkage tension and significantly reduce the probability of crack formation [28].

Application of finishing layers: The final passes form the finished weld profile. When restoring worn holes, 1–2 layers of hardfacing wear-resistant coating may be applied to the internal surface.

Slow cooling: Immediately after completion of welding and final peening, the repaired assembly is covered with thermal insulation in accordance with the protocol of section 3.2. The part is kept under insulation until it has fully cooled naturally to ambient temperature.

Strict adherence to the specified sequence moves cast iron welding from the category of high-risk operations to a reproducible, predictable, and technologically reliable process.

CHAPTER 4. RESTORATION OF GEOMETRIC ACCURACY BY MEANS OF MOBILE LINE BORING

After successful completion of welding operations, it is necessary to restore precise geometric dimensions and coaxiality of the holes. The use of mobile line boring and overlay welding systems is the most effective method for solving this task.

Principles of on-Site Precision Machining

The primary value of mobile machining lies in transferring the accuracy of a stationary machine tool fleet directly to the component being repaired [23]. This eliminates the need for complete disassembly of heavy assemblies, their transportation to the workshop and back, which is associated with enormous time and financial costs [43]. For large-scale machinery such as backhoe loaders, the ability to perform bore machining with an accuracy down to hundredths of a

millimeter directly on site drastically reduces downtime from weeks to days [23].

Technical Overview and Selection of Mobile Boring and Automated Overlay Welding Systems

The modern market for mobile boring systems covers the entire range of solutions — from basic units with manual feed to highly intelligent systems with CNC and integrated automatic overlay welding modules, which makes it possible to adapt the technology to a wide set of production scenarios [21].

The functional core of any such system is a boring bar made of high-strength alloy steel (typical grades 40Cr/42CrMo and analogues), which has undergone full-volume heat treatment followed by chrome plating; this combination provides the required bending stiffness during prolonged operation and high resistance to abrasive wear [44]. Drive units for rotation and axial feed are implemented in electric, hydraulic, or pneumatic configurations, which expands the applicability of the equipment under varying energy supply conditions and differing requirements for torque/feed rate [32, 45].

As a reference design it is reasonable to consider the Climax BB5000 system, which has in practice formed the industry standard for repair of mid-size machines. The basic parameters of the system include: a standard bar with a diameter of 57.2 mm (2.25") with the possibility of using adapters for smaller diameters; an operating boring range from 38.1 to 609.6 mm (1.5–24"); drive options — electric, pneumatic, or hydraulic — providing up to 881 N·m of torque on the bar; a patented mounting scheme on spherical bearing supports that allows rapid and accurate centering of the tool with compensation of installation irregularities up to 5° [46, 47].

Most modern platforms, including Climax solutions, provide integration with automatic overlay welding systems mounted on the same boring bar [43]. This approach enables automated restoration of the internal diameter with uniform deposit thickness and minimization of defects, forming a surface optimally prepared for subsequent finish boring; the critically important effect here is the conversion of a traditionally manual operation, dependent on the welder's qualification, into a reproducible and verifiable engineering procedure [44].

Table 4 describes the comparative technical characteristics of leading mobile boring systems.

Table 4. Comparative technical specifications of leading portable line boring systems (compiled by the author based on [22, 30, 44, 45, 49]).

Manufacturer / Model	Boring diameter range (mm)	Bar diameter (mm)	Drive type	Achievable accuracy (mm)	Key features
Climax BB5000	38.1 – 609.6	57.2 (standard)	Electric, pneumatic, hydraulic	< 0.03	Modular design, integration with Bore Welder, spherical supports

Pioneer RNK 2	50 - 400	n/a	n/a	n/a	Russian production, affordable price
AVANTECHNO	n/a	n/a	Electric	n/a	Integrated solution for boring and build-up welding, dielectric shaft
Shingare UNICORN-50	55 - 300	50	3.1 kW servo drive	≤ 0.02	CNC control, intelligent build-up welding, remote control

The selection of a specific complex is determined by the range of intended operations, the required level of accuracy, and acceptable budget constraints. When targeting professional, high-quality repair, it is rational to give preference to solutions with maximum boring bar rigidity, a high-performance drive (providing stable torque and feed), and confirmed compatibility with automated build-up welding.

Step-By-Step Machining Procedure

The setup and alignment stage of the system is critical, as it defines the ultimate accuracy of subsequent restoration. On both sides of the defective holes on the frame, bearing supports are fixed using welded pads or bolted joints [49]; a boring bar is passed through the supports and the bores are restored. Alignment of the bar axis with the required axis, which is common for all coaxial bores, is performed using centering cones, dial indicators, or laser alignment systems; as datums, the least worn areas of the bores or other frame elements ensuring reliable geometric referencing are selected [46, 48]. After adjustment, runout and coaxiality are checked, after which the supports and the bar are rigidly locked in the working position.

Rough boring begins immediately after the assembly is fixed and addresses two tasks: it removes excess weld-deposited metal and reveals possible welding defects, forming a uniform cylindrical base for subsequent operations. At this stage, stabilized feeds and depths of cut are set to ensure a predictable machining allowance and to minimize thermomechanical deformation in the cutting zone.

If the diameter is found to exceed the nominal value, automatic build-up welding is applied. The boring tool is replaced with a welding head that forms a continuous helical bead on the internal surface through a combination of system rotation and axial feed [49]. Build-up welding is performed until a diameter is achieved that is 2–3 mm smaller than nominal, in order to provide a technological allowance for finishing; the hardness of the deposited layer, depending on the material and process parameters, is 20–30 HRC [49]. Upon completion, intermediate stabilization and geometric inspection are carried out.

Finish boring is the final operation, performed with a new tool under high-precision feed and depth-of-cut parameters. The bore is brought to the dimension specified in the manufacturer’s specification; modern systems provide a diameter tolerance of up to 0.02 mm and a surface roughness parameter Ra 3.2 μm, which corresponds to or exceeds factory standards [22, 44]. Final inspection includes

measurement of the diameter along several generatrices, verification of coaxiality and cylindricity, and evaluation of surface roughness in accordance with the procedure.

If necessary, auxiliary operations are performed in the same setup, maintaining the common datum and accumulated accuracy: bosses are faced to ensure perpendicularity of the bore axis and correct seating of mating components, and grooves for retaining rings are machined using specialized tools [49]. Performing these operations in a single setup reduces re-clamping errors and increases the service life of the restored assembly.

After completion of the full machining cycle, the tooling is dismantled, and weld marks from the support pads are carefully cleaned with restoration of the original surface. As a result, an assembly is obtained with fully restored geometry and confirmed parameters of accuracy and surface quality, ready for assembly and further operation.

CHAPTER 5. QUALITY CONTROL, ASSEMBLY, AND COMMISSIONING

The final section closes the methodological loop, articulating in detail the procedures for verifying the quality of the restored component and offering organizations guidelines for the development of the corresponding competencies.

Post-Restoration Inspection

Upon completion of all welding and machining operations, the component is subject to rigorous acceptance inspection to confirm quality and compliance with requirements.

Final metrological inspection of dimensions: All restored diameters are measured using certified measuring instruments (bore gauges, micrometers). The coaxiality of spaced holes is evaluated using a control mandrel or with a laser system. Additionally, dimensional parameters of the boss end faces are verified. All measurements must fall within the tolerance fields specified in the OEM service documentation.

Hardness inspection: Portable hardness testing is performed in several zones: in the deposited weld metal, in the heat-affected zone (HAZ), and in the base metal at a distance from the weld. The objective is to exclude areas with abnormally high hardness (quench structures) in the HAZ, which would indicate a violation of the welding procedure. The hardness distribution profile must be smooth, except in cases where a wear-resistant hard alloy has been intentionally applied to the working surface.

Final non-destructive testing (NDT): The entire repaired zone is re-examined by penetrant testing (PT) or magnetic particle testing (MT) to confirm the absence of cracks that could have formed during welding, cooling, or machining. Detection of any cracks is a rejection criterion; the part is subject to rework.

Final Assembly

The assembly of the restored unit must be carried out with no less pedantry and technological discipline than the repair itself.

Installation of new components: Only new bushings, pins, and seals may be installed into restored bores. Reuse of worn mating parts is not permitted, as it accelerates wear of the restored surfaces and effectively nullifies the results of the performed work.

Proper fit: Bushings must be pressed in with the required interference fit using a hydraulic press or specialized mandrels. Impact-based installation methods are not permitted, as they may damage both the bushing and the bore.

Lubrication: Before installing the pins, all mating surfaces and cavities must be thoroughly filled with the manufacturer-recommended grease. This is critically important for ensuring long-term service life of the joint connection.

Operational Testing and Documentation

After the frame is mounted on the machine and installation of the rear boom is completed, a set of functional tests is performed.

Verification of motion range: The full kinematic cycle of the boom, stick, and bucket is assessed for all degrees of freedom — first in no-load mode, then under moderate load. The motion of the mechanisms must remain smooth, without jerks, binding, or extraneous noise.

Creation of a repair dossier: For each restored unit a detailed passport (dossier) is prepared, in which all stages of the process are recorded:

- results of incoming defectoscopy (defect maps, wear measurements);
- welding technology applied (electrode type, modes, temperature conditions);
- results of intermediate and final NDT;
- final dimensions after machining;
- photographic documentation of key stages.

Such documentation ensures full traceability of the repair intervention and serves as a valuable source of data for reliability analysis and planning of subsequent work. Accumulation of comparable statistics across the entire fleet of machines makes it possible to identify persistent

problems determined by model or operating conditions and to transition from reactive repair to proactive technical maintenance. For example, the analysis may reveal accelerated wear of a specific joint connection, which becomes the basis for adjusting the lubrication intervals or the inspection schedule.

CHAPTER 6. RECOMMENDATIONS FOR BUILDING INTERNAL RESTORATION CAPABILITY

The development of an internal competence center for restoration is a long-term strategic investment that requires a systematic, integrated approach, covering material and technical equipment and infrastructure, while the defining resource remains human capital.

Investment in Core Equipment and Facility Requirements

To deploy a work area for the restoration of bogie frames, the following basic set of equipment is required:

Mobile line boring and build-up welding system: the central element of the technology; selection is determined by the required working diameter range and the target accuracy class.

Welding equipment: inverter power sources for shielded metal arc welding (SMAW) and gas metal arc welding (GMAW/MIG-MAG), capable of reliably maintaining a stable arc at low welding currents.

Temperature control equipment: high-power propane or induction heaters for preheating; thermal insulation blankets for controlled slow cooling.

Equipment for preparation and cleaning: angle grinders and air carbon arc gouging units.

Non-destructive testing tools: kits for liquid penetrant testing and/or magnetic particle testing.

Measuring instruments: a set of calibrated bore gauges, micrometers, calipers and dial indicators.

Lifting equipment: an overhead crane or mobile crane with a lifting capacity of at least 1–2 t for safe handling of the frame.

The production area must have effective ventilation for the removal of welding fumes, provide sufficient space for the safe placement of equipment and the component being repaired, and comply with fire safety requirements.

Training of Technical Personnel and Skill Development Pathways

Even the most advanced equipment is powerless without specialists capable of extracting its full performance. The development of internal restoration capability begins with investment in human capital and implies a transition from the traditional maintenance and repair model focused on unit replacement to an engineering-oriented culture of life

cycle management and asset restoration. This paradigm shift increases operational performance and at the same time forms a more qualified and motivated team, transforming the repair unit from a cost center into a strategic asset of the company.

The recommended training program includes:

Theoretical training:

— Fundamentals of cast iron metallurgy: grades, properties, structure.

— Theory of cast iron welding: heat-affected zone (HAZ) issues, martensitic embrittlement, the role of alloying elements.

— Thermal cycle control technologies.

— Fundamentals of non-destructive testing (PT, MT).

Practical training:

— Development of cast iron welding skills using the recommended techniques (short beads, peening, temperature control).

— Hands-on training in installation, centering, and operation of the mobile line boring and build-up welding system.

— Execution of NDT and interpretation of results.

Specialists who complete such training are subject to qualification both by internal committees and, if necessary, by external certification bodies. This ensures consistently high work quality and turns maintenance personnel into restoration experts capable of solving complex technical problems and making a tangible contribution to the economic efficiency of the enterprise.

CONCLUSION

The proposed method for restoring sliding and swing frames of backhoe loaders is an integrated engineering concept based on an in-depth analysis of economic, metallurgical, and technological factors. It transforms the work from one-off emergency fixes into a controlled remanufacturing cycle that not only radically reduces costs compared to replacing the assembly, but also ensures that the resulting component exhibits performance parameters comparable to or exceeding the original.

The key findings of this guideline are as follows:

– Economic justification: Against the background of rising prices for new equipment and substantial losses caused by unplanned downtime, the development of in-house recovery capabilities is a strategically justified investment. Total cost of ownership (TCO) analysis shows that investments in tooling and personnel training pay back multiple times through the reduction of downtime and the extension of the service life of fixed assets.

– Technological foundation: The effectiveness of repairing

cast iron elements is entirely determined by strict adherence to the thermal welding regime. Preheating, the use of specialized nickel-based welding consumables, execution of short beads with subsequent peening, and controlled slow cooling are mandatory. These exact operations prevent embrittlement and crack formation in the heat-affected zone.

– Accuracy and quality: The use of modern mobile line-boring and buildup systems with automated surfacing restores the geometry and coaxiality of holes with factory-level precision, which guarantees the reliability and durability of the assembly after repair.

Implementation of the method provides the organization with distinct competitive advantages:

– Increase in operational readiness of the fleet through a sharp reduction in restoration time for critical components.

– Decrease in operating costs by eliminating the need for costly replacement with new parts.

– Growth of independence from external suppliers and the risks associated with them (lead times, price volatility).

– Improvement of technical personnel qualifications and the formation of an in-house center of engineering expertise.

Thus, mastering the restoration of swing frames is not merely an isolated technological procedure, but an effective instrument for improving asset management efficiency and reinforcing the long-term economic sustainability of the enterprise.

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