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METALLISKA MATERIAL

Removal of Weld Oxides (REWOX)
Sub report 3.
Assessment of the cleaning methods impact on global environment and work environment
Post weld cleaning of stainless-steel welds with electrolytical cleaning and handheld laser ablation

REWOX – Miljö- och arbetsmiljö

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1 INTRODUCTION

This report presents the results of work conducted within the Vinnova project REWOX (Dnr: 2022-01609). It forms part of Work Package 5 (WP5): Assessment of the environmental and occupational health impacts of cleaning methods. The report constitutes the deliverable titled "Comparative Environmental Analysis and Risk Assessment." This report summarizes the environmental and occupational impacts of three common weld cleaning methods: laser ablation, electrochemical cleaning, and chemical cleaning, and compiles a risk analysis from a user perspective.

Weld cleaning is essential for ensuring the integrity, aesthetics, and corrosion resistance of welded joints. In field operations, the choice of cleaning method significantly affects both the global environment and the local work environment.

Welding stainless steel creates an oxide film (heat-tint) on the surface and around the joint. The heat-tint is orders of magnitude thicker than the protective stainless steel oxide film (consisting of Cr, Mo, etc.). Weld oxides influence the corrosion resistance of stainless steel, and chemical pickling or abrasive mechanical processes are often used to remove them. Chemical pickling methods are hazardous, both for the environment and operator, especially during in-field assembly or repair work. Oxide removal by pickling paste is often conducted by specialized companies as it contains dangerous substances such as hydrofluoric acid, nitric acid, and sulfuric acid, and requires training, use of protective clothing and handling of residual products. Furthermore, it is increasingly hard to perform on high alloyed stainless steel due to the need for longer application time and more concentrated chemicals. There is also a risk of over-pickling which leads to a decrease in corrosion resistance. Compared to chemical pickling, a mechanical method is often less efficient and can result in insufficient corrosion resistance of the welded part. There is also a risk of damaging the surface through recontamination or scratching, which leads to initiation points for corrosion. The Rewox project aims to validate the effectiveness of newer cleaning options (electrochemical cleaning and laser ablation) in comparison to more conventional methods, by corrosion testing. The procedure for removal of weld oxides will include execution, parameter settings, cleaning time, avoidance of damaging base material and assessment of cleaned surface as acceptable/ nonacceptable.

To prevent ill health and promote a decent work environment is the fundamental aim of systematic work environment management, which is connected to the management of the organization. It is important to have clear procedures, knowledge, allocation of work environment tasks and cooperation at the workplace[1].

2 METHOD AND SYSTEM BOUNDARIES

A literature review was conducted to evaluate the environmental and occupational health impacts associated with various cleaning processes. This study focuses specifically on post-weld cleaning operations performed manually in the field using handheld equipment. Emphasis is placed on the occupational health and safety aspects, including acute toxic effects, potential risks to workers, and the release of hazardous substances into the environment. In addition, relevant regulatory frameworks are taken into account to ensure compliance and contextual relevance. This study does not take equipment manufacturing into account. Since a comparative Life Cycle Assessment (LCA) had already been carried out in the previous RFCS JOINOX project, no additional LCA was planned for the current study.

3 PREVIOUS WORK

In a previous study, RFCS JOINOX (RFSR-CT-2012-00034), a Life Cycle Assessment (LCA) of four post-weld cleaning methods for stainless steel was performed by Christina Jönsson and Anna Rúna Kristinsdóttir at Swerea IVF in 2014. The methods included in the study were: brushing, polishing, pickling paste, and pickling bath. The LCA included four scenarios for post-weld treatments:

1. Brushing
2. Brushing and polishing
3. Brushing and treatment with pickling paste
4. Brushing and treatment with pickling bath.

The goal was to evaluate and compare the environmental impacts of these methods, particularly in terms of climate change, acidification, eutrophication, and toxicity, while also considering their effect on product life extension. The functional unit in the study was 1 m^2 steel sheet with a 1 m long, 10 mm wide, weld and system boundaries were post-weld treatment only. Key findings from the study:

- Brushing alone had the smallest environmental footprint (short term) across most categories (climate change, acidification, eutrophication, toxicity).
- Brushing + pickling bath has the highest environmental burden (short term), due to:
    - Acid use and hazardous waste treatment.
    - The treatment of hazardous waste as well as textile cloth contributes to the overall impact in all cases. The acids used in the pickling as well as the neutralization agent, sodium hydroxide, contribute to the overall impact to some extent.
- When product life extension is factored in, brushing + pickling bath becomes the most environmentally efficient method over the full life cycle. It had the lowest impact per year of service, making it the most sustainable option over time.

Main contributors to impact:

- Hazardous waste treatment
- Use of acids and neutralization agents
- Textile waste from cleaning processes

Conclusions from the study:

- Brushing is environmentally preferable if minimal treatment is sufficient.
- Pickling bath, despite the higher immediate impact, offers the best long-term sustainability due to extended product life.
- Hazardous waste and textile use (a cloth of recycled cotton wet in ethanol used to wipe the surface) are significant contributors to environmental impact in all methods.
- Accurate life span estimation is critical for valid LCA conclusions.

4 METHODS FOR POST WELD CLEANING

The methods for post weld cleaning considered in this study include 1) Laser ablation, 2) Electrochemical weld cleaning, and 3) Chemical weld cleaning. The methods are briefly described below.

4.1 Laser ablation cleaning

LASER is an acronym for "*Light Amplification by Stimulated Emission of Radiation*". Laser ablation is a precise and powerful non-contact method that uses pulsed laser beams – typically in the nano second range – to remove contaminants from the weld surface. When the laser pulse is focused on a small area, the material absorbs the energy, leading to rapid heating, melting, and vaporization of the surface layer. This process causes the selective breakdown of molecular bonds and generates shock waves, which assist in dislodging and ejecting surface particles. The waste particles from the process can be removed through local ventilation.
Laser ablation systems typically use Class 4 lasers, which are the most hazardous category and require stringent safety measures. These high-energy systems pose risks such as eye and skin injury, fire hazards, and exposure to harmful fumes. Therefore, comprehensive safety protocols are essential to ensure the safety of both operators and equipment.

The laser ablation process requires specialized laser equipment and trained operators. The process control is high with adjustable parameters such as power and speed. Cleaning speed is high with a fast throughput. The surface impact is minimal with no contact and no residues and low waste generation (no chemicals used). The safety requirements are high with laser safety protocols and personal protective equipment (PPE). The environmental impact is considered low.

4.2 Electrochemical cleaning

In the electrochemical weld cleaning process, post-weld impurities such as rust, heat tints, and discoloration are removed from metal surfaces under the effect of mild electrolytic fluids and a weak electrical current[2]. Electrochemical cleaning involves using electrolytic solutions and a power supply. Chemical reactions reduce the oxides with the help of an applied alternating current, a carbon fiber brush, or a padded electrode. Alternating current minimizes the risk of affecting the surface and is often used during the cleaning step. The workpiece is then rinsed with a neutralizing liquid, a weaker alcohol solution. The passive layer is rebuilt at the same time as the oxide is removed as the oxygen is realized at the anode and reacts with for example chromium to create Cr-oxide. Various electrolytes, such as dilute phosphoric acid or a mixture of phosphoric and sulfuric acids, can be used. The welded part can either be immersed in acid or treated with hand-held devices. Manual weld cleaning is often done locally on the weld area and the heat-affected zone, which gives a precise approach with good control over how the electrolytes affect the surface. For hand-held devices, the acid solution is either pumped to a contact pad at the tip of a hand wand, or the tip is immersed in the solution. An earth lead connects to the hand wand, which is in contact with the workpiece, completing an electrical circuit. This locally heats the work surface and the acid solution, activating the cleaning process. The resulting fumes can be managed with local exhaust ventilation or an extraction system fitted with the cleaning unit. The resulting surface is smooth and typically only requires a simple wipe-down. Thanks to the size and shape of the contact pad, these devices can often reach welds that are inaccessible to mechanical cleaning methods. However, compatibility varies between manufacturers and models, particularly regarding weld types and plate thickness[3].
The set-up complexity is medium; power supply and electrodes are needed. Basic training for operators is sufficient, and the process control is moderate – it depends on the current and

electrolyte. The cleaning speed is moderate and depends on the weld size. The method is gentle on the surface, and the waste generation is low (some electrolyte waste). Safety requirements are medium – electrical safety and PPE required. The environmental impact is considered low with minimal waste generation.

4.3 Chemical weld cleaning

Chemical pickling is one of the most common methods of weld cleaning. The welded part can be immersed in a pickling bath. The use of pickling pastes arises from where the workpiece is too large to fit in a pickling bath or when the pickling is done in-field[3]. It usually involves the use of a special mixture referred to as pickling paste[4]. Operators who use pickling paste must be trained in how to safely handle and dispose of hazardous chemicals.

Application of pickling chemicals is carried out by brush, spray, or by submerging metal parts in specially constructed baths. Pickling paste can be applied using either a brush or a roller, both of which must be acid-resistant. While rollers tend to generate more splashes, brushing is generally preferred. Rollers are also less suitable for the contours of weld surfaces. The paste typically needs to be applied in a relatively thick layer, but it's important to avoid excessive application, especially when working overhead[3].

Excessive exposure to pickling paste – whether due to prolonged contact time, high concentration, or elevated temperature – can lead to over-pickling, which reduces the corrosion resistance of the treated surface. The use of pickling paste requires that personnel are properly trained in handling hazardous substances, equipped with appropriate personal protective equipment (PPE) such as full-body protection and a breathing mask, and capable of managing residual waste to prevent environmental contamination.

The set-up complexity for the process is low. The process control is low; it can be difficult to control uniformly. The cleaning speed is slow as is requires some dwell time. The method can be aggressive in the surface and may be scratched or stained. The waste generation and safety requirements are high with hazardous chemical handling and disposal. The environmental impact is high due to chemical runoffs and fumes.

5 SAFETY MEASURES FOR FIELD USE

For all methods, it is essential that Standard Operating Procedures (SOPs) are clearly defined for each stage of the process – setup, cleaning, shutdown, and maintenance. These procedures ensure that operations are carried out consistently, efficiently, and with the highest level of safety, regardless of whether the method used is laser-based, electrochemical, or chemical cleaning. Moreover, incident reporting protocols ensure quick response and documentation of any safety breaches. Personal protective equipment is described in Section 6.

5.1 Laser ablation cleaning

The complexity of laser ablation for weld cleaning involves a combination of physical, material, and operational factors that must be carefully managed to ensure effective and safe results.

Engineering controls are the primary and most effective safeguards when working with lasers. While not exhaustive, common examples include:

- Beam containment: Enclosing the laser and its beam path to prevent exposure. Use portable closures or beam shields.
- Assess restrictions: Limiting entry to laser-controlled areas through doors, barriers, or interlocks.
- Visual shielding: Using appropriate laser windows or protective screens to allow safe observation and containment[5].

Administrative controls involve policies, procedures, and training to ensure safe operation:

- Ensure operator certification and training.
- Implement standard operating procedures (SOPs).
- Designate a Laser Safety Officer (LSO) for oversight[6].

Environmental controls

- Set up local exhaust ventilation to remove ablation by-products.
- Keep fire extinguishers nearby.
- Monitor for reflected or scattered beams.

5.2 Electrochemical weld cleaning

Manual electrochemical weld cleaning is portable and can be done on- and off-site.
Engineering controls – physical modifications, or equipment features deigned to isolate or reduce exposure to hazards:

- Insulated and grounded equipment prevents electric shock from low-voltage systems.
- Local exhaust systems remove fumes and gases generated during cleaning.
- Spill containment systems prevent electrolyte leaks from spreading in uncontrolled environments.
- Non-conductive work surfaces reduce the risk of unintended current paths.
- Integrated fluid management prevents overuse or accidental discharge of electrolytic fluids.

Administrative controls

- Operator training includes handling of electrolytes, equipment set-up, and emergency response.
- Hazardous communication: Use of labels, signage, and safety data sheets (SDS) for all chemicals.

– Inspection and maintenance schedules: Regular checks on cables, applicator pads, and fluid containers.

Environmental controls. These manage the workspace to minimize exposure to chemical and physical hazards.

– Open-air or well-ventilated areas reduce accumulation of gases and vapors.
– Weather protection shields equipment and chemicals from rain, heat, or freezing conditions.
– Portable eye-wash stations and spill kits should be readily available for emergency use.
– Waste disposal systems ensure safe handling of used fluids and contaminated materials.
– Site layout planning keeps cleaning zones separate from pedestrian or high-traffic areas.

5.3 Chemical weld cleaning

Chemical pickling should only be performed by trained individuals as the risks are high. A full-body cover protecting every inch of the body is required at all times while using pickling paste. Due to the safety risks, the pickling process should be limited to a controlled and restricted area.

Engineering controls are the physical or mechanical systems designed to isolate workers from chemical hazards.

– Closed or semi-closed application systems minimize operator exposure to chemical cleaning agents.
– Chemical-resistant containment trays or mats prevent spills from spreading on uneven or outdoor surfaces.
– Portable fume extraction units capture vapor and fumes at the source, especially in confined or poorly ventilated areas.
– Non-reactive tools and containers to avoid unwanted chemical reactions.
– Emergency wash stations – portable eye wash and safety showers should be available on-site.

Administrative controls

– Chemical hazard communication to ensure all containers are labeled and SDSs are accessible.
– Training programs where field personnel must be trained in chemical handling, PPE use, spill response, and first aid.
– Work permit and supervision. Use hot work or chemical use permits when required and assign a safety supervisor for oversight.
– Exposure time limits. Rotate workers or schedule breaks to reduce prolonged exposure to fumes or skin contact.

Environmental controls

– Weather protection: use tents or covers to prevent rain or wind from spreading chemicals or interfering with application.
– Spill containment and clean-up kits must be readily available and suited to the specific chemicals in use.
– Waste collection and disposal: collect used chemicals and rinse water in designated containers for proper disposal according to local regulations.
– Site layout planning: designate chemical use zones away from storm drains, water bodies, or public walkways.
– Air monitoring (if applicable): for volatile or hazardous chemicals, use portable gas detectors to monitor air quality.

6 SAFETY RISKS AND PROTECTIVE EQUIPMENT

6.1 Laser ablation cleaning

Laser ablation is increasingly used in industrial settings for weld cleaning due to its precision and reduced chemical waste. However, it involves significant safety considerations, particularly regarding optical radiation, airborne contaminants, and mechanical hazards. In Sweden, the use of such equipment is regulated under the Swedish Work Environment Authority’s provisions, notably AFS 2023:11 (Use of Work Equipment) and AFS 2001:3 (Use of Personal Protective Equipment).

Laser ablation operations pose both health and safety hazards. Health risks include exposure to metal fumes and UV radiation, while safety hazards involve burns, eye injuries, and electrical shock. Fortunately, many of these risks can be effectively managed through proper work practices and the use of personal protective equipment (PPE).

The laser ablation cleaning method does not involve any acids, but it does involve dangerous radiation. In the field of artificial optical radiation, there are several risks that can arise for those exposed to it. The main risk is eye damage, such as retinal injuries and eye diseases like cataracts. Other risks include skin irritation, burns, and light sensitivity.

It is also well-known that UV radiation can cause skin cancer. It is important to follow work-place safety regulations to minimize these risks and protect workers' health[7].

Class 4 lasers can cause damage to eyes and skin, even if you look at the laser beam when it appears as a bright spot on a matte surface. These lasers can also be a fire hazard[8].
Laser viewing hazard - The three primary modes of laser viewing are described below: direct, specular, and diffused, and the risks associated with it.

Direct viewing – involves direct exposure of the eyes or the skin to the laser beam. It is considered the most dangerous form of exposure, reflex time for accidental eye exposure is approximately 0.25 seconds (blink response). Intentional direct viewing is strictly prohibited, and PPE is designed to protect against unintentional direct exposure only.

Specular viewing – occurs when laser beams reflect off smooth, mirror-like surfaces, for example stainless steel. These reflected beams can retain full intensity. Specular reflection is classified as equally hazardous as direct viewing and must be prevented through engineering controls and proper workspace design.

Diffused viewing – arises from reflections off rough or matte surfaces such as wood or unfinished walls. The intensity is typically lower compared to direct or specular reflections. Despite its lower intensity, Class 4 lasers can cause fires through diffused reflection. Prolonged or close-range exposure may still result in permanent biological harm.
All three forms of laser viewing pose serios safety threats. While direct and specular viewing are high-risk activities, even diffused reflections can cause lasting damage or ignite fire under certain conditions.

Occupational risks. Laser ablation systems, especially Class 3B and Class 4 lasers, pose several risks:

- Eye injuries from direct or reflected laser beams

- Skin burns from high-intensity radiation
- Inhalation of toxic metal fumes and ultrafine particles
- Noise exposure from pulsed laser systems
- Electrical and mechanical hazards from equipment operation

Protective equipment required. Laser ablation weld cleaning is generally considered safer than chemical pickling, but it still requires specific personal protective equipment (PPE) due to the risks associated with high-energy laser systems, airborne particulates, and optical radiation. According to the Swedish Work Environment Authority (Arbetsmiljöverket), laser ablation for weld cleaning is subject to strict safety and protective equipment requirements under the AFS 2023:11[9] and AFS 2001:3[10] regulations. AFS 2023:11 governs the use of work equipment, including laser systems, and mandates risk assessments, training, and safety measures. AFS 2001:3 outlines the general requirements for personal protective equipment in the workplace. Employers must ensure that PPE is appropriate, maintained, and used correctly, and that workers are trained in its use.

Personal protective equipment (PPE) requirements

Eye Protection

- Laser safety goggles rated for the specific wavelength and power
- Must comply with ISO 19818-1:2021[11] or equivalent standards

Skin and Body Protection

- Flame-resistant clothing covering arms and legs
- Non-melting materials to prevent thermal injury
- Protective gloves against heat and mechanical hazards
- Steel-toe boots or protective footwear to guard against dropped tools or materials.

Respiratory Protection

- Local exhaust ventilation (LEV) is the primary control
- If LEV is insufficient, use P3/PAPR[1]

Hearing Protection

- Required if noise levels exceed safe thresholds
- Use of earplugs or earmuffs as appropriate

6.2 Electrochemical weld cleaning

Electrolytic weld cleaning is considered much safer than chemical pickling as it is not associated with negative effects on human health and environment[4], but it still involves specific safety risks and require appropriate protective equipment – especially in field applications. Compared to using chemical pickling, the requirement for personal protection equipment is less extensive (gloves, glasses, and work clothes).

Personal protective equipment (PPE) requirements

Eye Protection

[1] *a PAPR is a type of respirator that uses a battery-powered blower to pull air through filters and deliver it to the user. It provides protection against airborne contaminants and is commonly used in healthcare, industrial, and hazardous environments. P3 filters are capable of filtering 99.95% of airborne particles, including dust, aerosols, and pathogens. This combination offers high-level respiratory protection, suitable for environments with very hazardous airborne particles.*

– Safety goggles or face shield to prevent eye contact with splashes or vapors

Skin and Body Protection

- Chemical-resistant gloves to protect hands from electrolyte exposure.
- Protective clothing (lab coat or apron) to shield skin from chemical contact.
- Insulated footwear to reduce the risk of electric shock in wet conditions.

Respiratory Protection

- If needed, respirator in confined spaces or poor ventilation.

6.3 Chemical weld cleaning

Hydrofluoric acid (HF) and nitic acid (HNO3) are the two main types of acids contained in pickling paste, and they are extremely dangerous for human internal organs, skin, bones, and respiratory system. A range of short and long-term harmful effects can be caused by inhalation of vapors or direct contact with pickling acids. Some of the symptoms can occur 24 hours after contamination, while others such as lung cancer can appear years after exposure[12]. Some formulations also contain sulfuric acid (H2SO4).

Hydrofluoric acid dissolves oxides and helps remove chromium depleted layers. It is a highly corrosive, toxic, and reactive chemical, and it can penetrate deep skin tissue and cause liquefactive necrosis and release cellular products. Exposure to hydrofluoric acid, whether through ingestion, inhalation of fumes, or vapors, can result in severe health issues. These include skin burns, eye injuries, acute respiratory symptoms, and systemic fluoride toxicity. The latter can affect the cardiovascular, pulmonary, renal, and neuromuscular systems, leading to electrolyte imbalances, enzyme inhibition, cardiac arrhythmias, and potentially death. Contact with diluted hydrofluoric acid solutions can result in severe and excruciating burns. These burns may not be immediately apparent, as it can take up to 24 hours for the pain to manifest. The acid can continue to damage tissue even after initial attempts to wash it off the skin. Additionally, even small amounts of diluted hydrofluoric acid can cause irreversible eye damage[3].
Routes of exposure: Inhalation of vapor or aerosols, dermal contact with liquid HF, Ocular exposure through splashes, ingestion (rare but extremely hazardous).

Symptoms of exposure:

- Inhalation: coughing, wheezing, chest tightness, pulmonary edema, respiratory failure
- Skin contact: severe burns with delayed pain, tissue necrosis, hypocalcemia (low calcium levels)
- Eye contact: severe irritation, corneal burns, potential blindness
- Systemic: Hypocalcemia and hypomagnesemia, cardiac arrhythmias, potential fatal cardiac arrest

Hydrofluoric acid is uniquely hazardous due to its ability to cause both local tissue damage and systemic toxicity. Proper handling procedures, use of protective equipment and emergency protocols are essential to mitigate health risks[13,14].

Nitric acid acts as an oxidizing agent to help dissolve iron and other contaminants. It is extremely corrosive and can cause lesions on the skin, eyes, and mucous membranes upon contact. Exposure to nitric acid can result in acute and chronic health issues. The severity of these lesions depends on both the duration of exposure and the concentration of the acid[15].

Routes of exposure: Inhalation of vapors or aerosols, skin contact with liquid nitric acid, eye contact with splashes, ingestion (accidental or occupational).

Symptoms of exposure:

- Respiratory: coughing, chest tightness, shortness of breath, pulmonary edema
- Skin contact: severe burns, yellow staining due to xanthoproteic reaction
- Eye contact: irritation, burns, potential blindness
- Systemic: headache, dizziness, nausea, fatigue

Chronic health effects:

- Chronic bronchitis
- Increased airway sensitivity
- Potential long-term lung damage[16,17]

Sulfuric acid enhances the cleaning effect and helps in removing heavy oxides. It is highly corrosive to skin, eyes, and mucous membranes. Exposure to sulfuric acid can cause a range of symptoms depending on the route and severity of contact. If exposure occurs immediate medical attention is critical.

Symptoms of exposure:

- Respiratory: coughing and choking, chest tightness or pain, shortness of breath, dizziness or weakness, cyanosis (bluish skin, lips, or nails), pulmonary edema in severe cases.
- Skin contact: severe burning sensation, redness, blistering, and tissue damage, drainage from affected areas, long-term scaring if not treated properly.
- Eye contact: intense pain and burning, tearing and redness, vision loss or permanent eye damage.
- Systemic: headache, nausea and vomiting, fatigue or confusion (in severe cases).

Protective equipment required: Before using pickling paste, a risk assessment must be carried out to determine the need for personal protective equipment (PPE). As part of this process, consult the product´s Material Safety data sheet (MSDS), which should specify the required PPE. If the MSDS lacks this information, contact the supplier for guidance. Once the assessment is complete, ensure that all identified PPE is provided to the relevant personnel[3]. Extensive personal protection equipment and clothing are required as the pickling paste contains hazardous chemicals that are extremely harmful for internal organs, skin, bones, and the respiratory system and can lead to both acute and long-term injuries.

Personal protective equipment (PPE) requirements

Eye Protection

- Face shield and goggles to prevent eye and face contact with splashes or vapors

Skin and Body Protection

- Chemical-resistant gloves to protect hands from acid burns and chemical absorption.
- Acid-resistant apron or suit to shield body and clothing from corrosive chemicals.
- Rubber boots to prevent chemical contact with feet and lower legs.

Respiratory Protection

- Respirator (acid vapor rated) to protect lungs from inhaling harmful fumes, especially in enclosed spaces.

7 IMPACT ON GLOBAL ENVIRONMENT

7.1 Laser ablation cleaning

Environmental benefits

- No hazardous chemicals. Unlike pickling, laser ablation does not use corrosive acids, eliminating the risk of toxic wastewater and acidic runoff.
- Minimal waste generation. Laser cleaning is a dry process, producing no liquid waste and significantly less solid waste compared to abrasive or chemical methods.
- Selective and precise. The process is highly localized, reducing the risk of over-cleaning or damaging surrounding materials, which can reduce material waste and rework[18].

Environmental concerns

- Airborne emissions. Laser ablation can release ultrafine particles, metallic fumes, and organic vapors from coatings or contaminants on the weld surface. These may require filtration or fume extraction systems to prevent environmental release[19].
- Energy consumption. High-powered lasers consume significant electricity, which may offset some environmental benefits depending on the energy source used[18].
- Noise and light pollution. Pulsed laser systems can generate high-frequency noise and intense light emissions, which may require shielding and soundproofing in sensitive environments[20].

Mitigation strategies

Use local exhaust ventilation (LEV) with HEPA filters to capture airborne particles. Operate in enclosed or shielded environments to contain emissions and noise. Source electricity from renewable energy to reduce carbon footprint.

7.2 Electrochemical weld cleaning

Electrochemical weld cleaning is widely regarded as a green technology as it aligns with waste minimization and pollution prevention principles. It is suitable for on-site use without the need for hazardous chemical handling. It supports worker safety and environmental compliance in regulated industries.

Environmental benefits

- Electrochemical weld cleaning uses mild electrolytes, often based on phosphoric acid and citric acid, which are significantly less hazardous than hydrofluoric or nitric acid used in pickling. Wastewater generated is less toxic and easier to neutralize or recycle[21].
- Low air emissions. The process produces minimal airborne emissions, mostly water vapor and trace amounts of metal ions. No harmful acid vapors or volatile organic compounds are released[21].
- Energy efficiency. Electrochemical systems operate at low voltages and currents, making them energy-efficient compared to laser systems.
- No abrasive or solid waste. Unlike mechanical or abrasive cleaning, electrochemical methods do not generate dust or solid waste, reducing the need for filtration or disposal.

Environmental concerns

- Electrolyte disposal. While less hazardous, spent electrolytes still require proper disposal or treatment to prevent metal ion contamination in water systems.

- Equipment cleaning and maintenance. Electrodes and applicators must be cleaned regularly, which may generate small volumes of rinse water containing metal residues.

Mitigation strategies
Use of biodegradable or low-toxicity electrolytes (e.g., citric acid -based solutions) and avoid heavy metal additives or aggressive acids that complicate disposal. Implement closed-loop electrolyte circulation to minimize waste generation, reuse electrolyte after filtration, reduce water and chemical consumption. Treat rinse water and spent electrolyte using neutralization tanks, Ion exchange or filtration systems, metal recovery units to prevent contamination of water systems. Use low-voltage, high-efficiency power supplies and automate cleaning cycles to reduce idle energy use. Regularly clean and maintain electrodes to extend equipment life, reduce contamination, and improve cleaning efficiency.

7.3 Chemical weld cleaning

Air pollution and waste materials pose a serious threat to the environment[2]. The pickling process produces waste in the form of rinsing water and exhausted pickling solutions. The waste is considered hazardous as it includes nitric acid, hydrofluoric acid, and heavy metals residues[4]. This is especially important when welding takes place in the field where handling pickling paste and residual products is extra difficult, or for products to be used for food and beverages. Improper disposal of spent pickling liquor poses environmental hazards due to its acidity and metal content.

Environmental benefits
- Reduced mechanical abrasion. Chemical cleaning avoids grinding or brushing, which can generate airborne particles and noise pollution.
- Improved surface passivation, especially for stainless steel, chemical cleaning can enhance corrosion resistance, extend the life span of components and reduce material waste.
- Selective cleaning allows targeted treatments without affecting surrounding areas, minimizing unnecessary material removal.

Environmental concerns
- Chemical runoffs and spills of acids like nitric or hydrofluoric acid can contaminate soil and water if not properly contained.
- Air pollution: vapors from volatile chemicals contribute to local air quality degradation and may pose respiratory risks to nearby workers and wildlife.
- Waste disposal: used chemicals and rinse water often contain heavy metals and must be treated as hazardous waste.
- Packaging and transport: chemical containers contribute to plastic and hazardous waste if not recycled or reused.

Mitigation strategies
Use closed-loop application systems to minimize exposure and prevent spills. Install portable fume extraction units to capture vapors at the source. Employ secondary containment trays under work areas to catch drips and spills. Maintain inventory tracking to avoid overuse or expired chemicals. Conduct cleaning in designated zones away from drains and natural water sources. Use neutralization agents and spill kits on-site. Partner with certified waste handlers for chemical disposal.

8 LEGAL REGULATIONS

In Sweden, the regulatory landscape for weld cleaning methods – particularly laser ablation, electrochemical cleaning, and chemical cleaning – is shaped by both national environmental and occupational safety laws and EU directives. Here's a summary based on current initiatives and standards:

Swedish regulatory context

Laser ablation is regulated under: Swedish work environment authority (Arbetsmiljöverket) and EU Machinery Directive. The key regulation is AFS 2023:4 – Products, machines: Covers safety requirements for machines, including laser systems.

Key requirements:

- Must comply with laser safety standards (e.g., EN 60825-1).
- Requires risk assessments, laser safety officer (LSO) designation, and PPE.
- Environmental impact is minimal, but fume extraction may be required depending on material.

In addition to AFS 2023:11, AFS 2009:7 – Artificial optical radiation[22] issued by the Swedish Work Environment Authority provides detailed requirements for managing risks associated with artificial optical radiation, including laser systems. It mandates exposure limits, risk assessments, protective equipment, and medical controls for workers exposed to Class 3B and Class 4 lasers. Employers must ensure that laser operations comply with these regulations to prevent eye injuries, skin damage, and long-term health effects such as cataracts and skin cancer.

Electrochemical cleaning is regulated under: Swedish chemicals agency (Kemikalie-inspektionen) and work environment authority.

Key requirements:

- Use of non-toxic electrolytes is encouraged.
- Equipment must meet electrical safety standards.
- Wastewater must be handled according to local environmental regulations.

Chemical cleaning (Pickling) is heavily regulated due to hazardous substances like nitric and hydrofluoric acid.

Key requirements:

- Must comply with REACH and CLP regulations for chemical safety.
- Requires ventilation, spill containment, and hazardous waste disposal protocols.
- Increasingly discouraged for in-field use due to environmental and health risks.

8.1 Laser ablation cleaning

Activities where workers are exposed to artificial optical radiation, which may pose safety or health risks to workers' eyes and skin are regulated in chapter 12 - Artificial Optical Radiation - in The Swedish Work Environment Authority's Regulations and General Recommendations (AFS 2023:10)[23] on Risks in the Work Environment. These regulations and recommendations aim to identify, evaluate, and mitigate risks in the workplace to ensure the safety and health of employees. They cover various aspects of occupational hazards, including physical, chemical, biological, and ergonomic risks, and provide guidelines for systematic work environment management[6]. To use Class 4 lasers professionally, you must obtain a permit from the Swedish Radiation Safety Authority (Strålsäkerhetsmyndigheten).

Class 4 Lasers: Surgical Lasers, Industrial Material Processing Lasers, Laser Shows
This class includes all lasers that are more powerful than Class 3B lasers. There is no upper limit to the output power of a Class 4 laser. A permit from the Swedish Radiation Safety Authority (Strålsäkerhetsmyndigheten) is required to use lasers in this class for entertainment, art, and advertising, or if the use involves exposure to public spaces or airspace. Strong laser pointers in this class are prohibited unless you have a special permit from the Swedish Radiation Safety Authority. A permit is also required for handheld lasers that are used or possessed in public spaces[7]. According to Section 13 of the Swedish Radiation Safety Authority's Regulations and General Advice (SSMFS 2014:4) on Lasers, Strong Laser Pointers, and Intense Pulsed Light. A permit is required for Class 3B or Class 4 lasers for[24]:

- Use in entertainment, art, or advertising,
- Use that involves exposure to public spaces or airspace, or
- Possession or use of handheld lasers in public spaces, within school areas where teaching is conducted, or in vehicles in public spaces.

8.2 Electrochemical weld cleaning

Employers must conduct risk assessments and implement systematic work environment management (AFS 2023:1). Waste fluids must be collected and disposed of according to Swedish environmental regulations.

8.3 Chemical weld cleaning

The use of pickling chemicals is often strictly regulated by law due to the presence of harmful acids. The regulations include protective safety measures, methods of application, waste disposal, and production site preparation. Employers must conduct risk assessments and implement systematic work environment management (AFS 2023:1). Waste fluids must be collected and disposed of according to Swedish environmental regulations.

9 SUMMARY

This summary presents a comparative analysis of three weld cleaning methods – laser ablation, electrochemical cleaning, and chemical cleaning – based on their environmental impact, occupational safety, waste generation, regulatory burden, setup complexity, cleaning speed, surface impact, and field suitability.

Each method was analyzed in terms of its environmental footprint, safety risks, regulatory compliance, and practical suitability for field use. Laser ablation emerged as a highly precise and environmentally favorable method, though it requires stringent safety protocols due to the use of Class 4 lasers. Electrochemical cleaning offers a balance between safety, environmental performance, and field applicability, using mild electrolytes and low-voltage systems. Chemical cleaning, while effective in oxide removal and surface passivation, poses significant environmental and health hazards due to the use of strong acids such as hydrofluoric and nitric acid. The following table summarizes the comparative performance of the three methods across key criteria.

Table 1 - Comparison table

	Laser Ablation	**Electrochemical Cleaning**	**Chemical Cleaning**
Environmental Impact	Low (no chemicals, minimal waste, but energy use and emissions)	Low (mild electrolytes, low emissions)	High (hazardous chemicals, toxic waste)
Occupational risk	High (Class 4 laser hazards, PPE and training required)	Moderate (electrical safety, PPE required)	High (acid burns, inhalation risks, extensive PPE)
Waste generation	Minimal (dry process, no liquid waste)	Low (some electrolyte waste)	High (hazardous waste and runoff)
Regulatory burden	High (requires permits, compliance with laser safety standards)	Moderate (chemical safety and disposal regulations)	High (strict chemical handling and disposal laws)
Setup complexity	High (specialized equipment and trained operators)	Medium (requires power supply and electrodes)	Low (simple application but high safety requirements)
Cleaning speed	Fast (high throughput)	Moderate (depends on weld size)	Slow (requires dwell time)
Surface impact	Minimal (non-contact, no residues)	Gentle (smooth finish, low risk of damage)	Aggressive (risk of over-pickling and corrosion)
Field suitability	Moderate (portable units exist, but safety controls needed)	High (portable and precise for field use)	Low (limited by safety and environmental constraints)

10 RESULTS AND DISCUSSION

The comparative analysis reveals that laser ablation and electrochemical cleaning are both viable alternatives to traditional chemical cleaning, particularly in field applications where safety and environmental compliance are critical. Laser ablation, while requiring significant investment and operator training, offers a clean, residue-free process with minimal environmental impact. Electrochemical cleaning provides a practical and safer alternative with moderate setup complexity and low waste generation.

Chemical cleaning, despite its effectiveness in oxide removal and surface passivation, is increasingly constrained by regulatory and environmental considerations. The use of hazardous acids necessitates extensive protective measures, controlled environments, and specialized waste disposal protocols, making it less suitable for field use.

Overall, the findings support a transition toward more sustainable and operator-friendly cleaning technologies, with laser ablation and electrochemical methods offering promising pathways for reducing the environmental and occupational health burdens associated with weld cleaning.

11 CONCLUSIONS

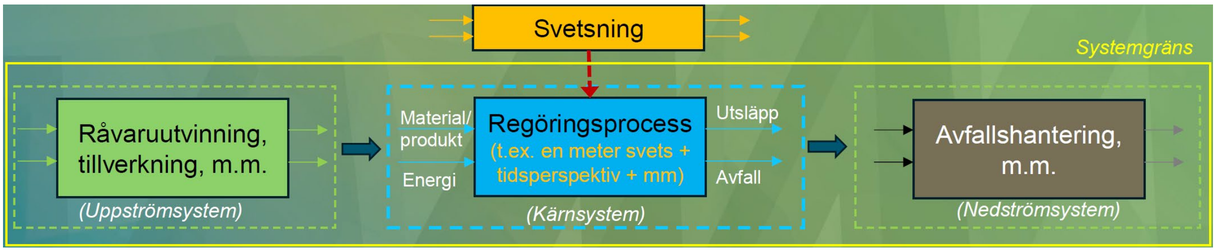
This assessment provides a comparative analysis of three post-weld cleaning methods – laser ablation, electrochemical cleaning, and chemical cleaning – with respect to their environmental and occupational health implications. The findings serve to inform field operations, regulatory compliance, and future development in surface treatment technologies.

- **Laser ablation** cleaning is identified as an effective and environmentally sustainable method. It offers minimal surface impact, eliminates the need for hazardous chemicals, and generates negligible waste. However, its implementation in field settings requires stringent safety protocols due to associated risks with Class 4 laser radiation.
- **Electrochemical weld cleaning** presents a balance between cleaning efficiency and occupational safety. It employs mild electrolytic solutions and low electrical energy, resulting in reduced toxic emissions and lower waste generation.
- **Chemical weld cleaning (pickling)** remains the most effective for corrosion resistance and oxide removal but leads to significant occupational health risks due to the use of hydrofluoric and nitric acid. This method entails elevated environmental hazards, complex waste handling procedures, and requires strict adherence to safety and regulatory standards.

Overall, the report concludes that while chemical cleaning methods retain technical efficiency, their use in field operations should be limited. Electrochemical and laser-based cleaning techniques present viable and safer alternatives. These methods align more efficiently with current regulatory frameworks and sustainability goals, supporting improved environmental stewardship and occupational health outcomes in industrial practices.

12 SUGGESTED CONTINUED WORK

In a bigger picture, the environment and work environment aspect covered in this report could further be placed in a context including economical and technical perspectives. This could form a larger life-cycle analysis that would better holistically compare the methods not only for companies practicing the cleaning methods, but also for constructors or regulatory bodies that are relevant to the entire welding value chain. The diagram below showcases one system with slightly expanded boundaries to those of this project.



13 ACKNOWLEDGEMENTS

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APPENDIX A - REGULATORY APPENDIX FOR WELD CLEANING METHODS IN SWEDEN

A.1 Laser ablation cleaning

Regulatory authority:
- Swedish work environment authority (Arbetsmiljöverket)

Key regulations:
- AFS 2023:4 – Products – Machines: Governs the design and safe use of machinery, including laser systems. Requires risk assessments, CE marking, and compliance with harmonized standards such as EN 60825-1.
- AFS 2023:11 – Work equipment and personal protective equipment: Specifies requirements for PPE and safe use of work equipment, including laser safety goggles, signage, and operator training.
-AFS 2009:7 – Artificial Optical Radiation: Regulates exposure to artificial optical radiation, including laser systems. Covers risk assessment, exposure limits, protective measures, and medical surveillance for workers exposed to Class 3B and Class 4 lasers.
- EN 60825-1: International standard for laser safety, including classification, labeling, and exposure limits. Harmonized under EU law and applicable in Sweden.

Environmental oversight:
-Subject to the Swedish environmental code, which mandates precautionary measures and pollution control for any activity that may impact human health or the environment.

A.2 Electrochemical cleaning

Regulatory authorities:
- Swedish chemicals agency (Kemikalieinspektionen)
- Swedish work environment authority

Key regulations:
- AFS 2023:11: Covers electrical safety and PPE for handling electrochemical equipment in field operations.
- REACH Regulation (EC) No 1907/2006: Requires registration, safe handling, and documentation of chemical substances used in electrolytes.
- CLP Regulation (EC) No 1272/2008: Governs classification, labeling, and packaging of chemicals to ensure safe use and communication of hazards.

Environmental oversight:
- Wastewater and spent electrolytes must be managed under the Swedish Environmental Code, which enforces proper disposal and pollution prevention.

A.3 Chemical cleaning (Pickling)

Regulatory Authorities:
- Swedish chemicals agency
- Swedish environmental protection agency (Naturvårdsverket)
- Swedish work environment authority

Key regulations:
- AFS 1992:9 – Fusion welding and thermal cutting: Addresses risks from fumes, chemical exposure, and fire hazards during welding and related processes.
- REACH & CLP regulations: Strictly regulate hazardous substances like nitric and hydrofluoric acid, requiring safety data sheets (SDS), proper labeling, and risk management.
- Swedish environmental code:
- Enforces the precautionary principle, polluter pays principle, and product choice principle.
- Requires operators to assess environmental risks before starting and throughout the activity.
- Supervisory authorities may issue bans, permits, or corrective actions based on these principles.

Contaminated sites oversight:
- Improper chemical handling can lead to site contamination, which falls under remediation protocols outlined by Swedish Environmental Protection Agency.

A.4 General environmental framework

Swedish environmental code:
- Applies to all activities that may affect the environment or human health.
- Promotes sustainable development through:
- Precautionary principle: Prevent harm before it occurs.
- Polluter pays principle: Responsibility for environmental damage.
- Product choice principle: Preference for less harmful alternatives.
- Resource management: Encourages recycling and efficient use of materials.
- Used by authorities to issue permits, bans, and enforce compliance.

References and resources:

Swedish environmental code – Naturvårdsverket: https://www.naturvardsverket.se/en/laws-and-regulations/the-swedish-environmental-code/

Kemikalieinspektionen – Chemical Safety: https://www.kemi.se/

Arbetsmiljöverket – Föreskrifter: https://www.av.se/arbetsmiljoarbete-och-inspektioner/publikationer/foreskrifter/

Naturvårdsverket – Environmental Oversight: https://www.naturvardsverket.se/en/

APPENDIX B DESCRIPTION OF THE PROGRAMME

Projektet REWOX är en del av det strategiska innovationsprogrammet

Metalliska material

Det strategiska innovationsprogrammet **Metalliska material** är ett samverkansprogram mellan Jernkontoret, Svenskt Aluminium och Gjuteriföreningen som delfinansieras av VINNOVA och löper under åren 2013–2025.

Programmets syftar till att förverkliga den strategiska innovationsagendan **Nationell samling kring metalliska material** vars långsiktiga vision är att svensk metallindustri ska vara ett centralt element i världens strävan att forma en bättre framtid. Det innebär att dess erbjudanden till kund måste ligga i den absoluta tekniska, ekonomiska och miljömässiga framkanten och utvecklas av drivna och engagerade människor. Samtidigt ska tillverkningsmetoderna ha ett så litet miljömässigt fotavtryck som det bara är möjligt.

Programmet stödjer insatser inom sju insatsområden för förnyelse, tillväxt och ökad konkurrenskraft:

1. Utveckla erbjudandet!
2. Öppna värdekedjan!
3. Öka materialutvecklingstakten!
4. Öka flexibiliteten!
5. Öka resurseffektiviteten!
6. Minska miljöpåverkan!
7. Öka kompetensen och attraktiviteten!

Programmets insatser består förutom FoU-projekt som valt i öppna utlysningar, även av strategiska projekt och aktiviteter.

Programkontor, med ansvar för ledning och administration av programmet, är Jernkontoret.

Jernkontoret

The Swedish Iron and Steel Producers' Association

Since its foundation in 1747, Jernkontoret has been owned jointly by the Swedish iron and steel companies. Jernkontoret represents Sweden's iron and steel industry on issues that relate to trade policy, research and education, standardisation, energy, the environment and sustainability as well as transportation issues. Jernkontoret also manages the joint Nordic research on steel. In addition, Jernkontoret draws up statistical information relating to the industry and carries out research into the history of mining and metallurgy.

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