Journal of Electrotechnology, Electrical Engineering and Management (2026)
Clausius Scientific Press, Canada
DOI: 10.23977/jeeem.2026.090107
ISSN 2560-6697 Vol. 9 Num. 1

Cause analysis and preventive control strategy of welding defects in on-site installation of chemical equipment

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Keywords: Chemical equipment; On-site installation; Welding defects; Cause analysis; Quality control

Abstract: In order to effectively prevent safety accidents in chemical production and ensure the safety, reliability and service life of chemical equipment operation, high attention should be paid to welding quality during on-site installation. Based on the actual conditions of on-site installation and welding of chemical equipment, this article systematically reviews five typical defects, namely cracks, porosity, slag inclusions, incomplete fusion, and undercut, and their causes, and proposes a full life cycle prevention and control system for welding defects, focusing on pre-welding preparation, welding process monitoring, post-welding detection and analysis, and defect repair. This approach effectively mitigates adverse impacts stemming from complicated site conditions, variable operational environments and unpredictable human factors during welding defect prevention and control, thereby guaranteeing the inherent safety of welding quality.

1. Introduction

Chemical production activities often involve high temperatures, high pressures, flammable and explosive, and highly corrosive media, which impose extremely high requirements on the structural integrity and sealing of chemical equipment. In the on-site installation of chemical equipment, welding, as a core process, is different from welding in the factory. The on-site working environment is complex and changeable, the space is limited, and the construction conditions are uneven, which increases the difficulty of welding control. If there are welding defects, it will not only directly lead to the malfunction of the chemical equipment, but also cause huge economic losses and pose a serious threat to the safety of people's lives and the ecological environment.

2. On-site installation welding defects of chemical equipment and their causes

2.1 Cracks

Based on the on-site welding practice of chemical equipment, cracks are one of the most dangerous defects. Once formed, they will continue to extend during the operation of the equipment. If not dealt with in time, they will lead to the fracture and failure of the equipment. Cracks can be classified into hot cracks and cold cracks based on their formation time and cause. Hot cracks often form during the high-temperature stage of welding. During the welding process, mismatches between the welding material and the base material, excessive welding current, too fast welding speed, too small bevel Angle or too large gap of the welding joint, and insufficient preheating of on-site welding can all cause cracks. Cold cracks mainly occur during the cooling phase after welding and appear within hours or even days after the welding is completed. The main causes of such cracks include the formation of large microstructure stress due to the martensitic transformation of the weld metal caused by excessive cooling rate, the formation of hard and brittle microstructure after welding due to excessive carbon content in the base metal, the accumulation of hydrogen-induced cracks at weld defects due to excessive hydrogen content during welding, and the long-term accumulation of residual stress due to untimely post-weld stress relief heat treatment.

2.2 Porosity

Porosity occurs when bubbles in the molten pool fail to escape during solidification during welding, a welding defect that reduces the tightness, strength, and toughness of the weld seam and may also be the starting point of corrosion, affecting the sealing performance and corrosion resistance of chemical equipment. The main causes of its formation include: (1) The electrode and wire are damp and not dried as required, and during welding, the moisture decomposes to produce hydrogen gas that mixes into the weld seam to form porosity; (2) Inadequate purity of the welding shielding gas or improper flow control and insufficient shielding range, which causes air to enter the welding pool and form porosity upon cooling; (3) too small welding current, too fast welding speed, too low temperature of the molten pool, resulting in gas not being able to escape in time due to improper control of process parameters, thus forming weld seams; (4) Excessive humidity at the welding site, with moisture in the air entering the molten pool and causing porosity.[1]

2.3 Slag inclusions

If the slag in the molten pool does not fully rise to the surface during the welding process and remains inside the weld seam or at the junction of the weld seam and the base metal, it will cause slag inclusion, disrupt the continuity of the weld seam, reduce the strength and toughness of the joint, and even cause cracks. In the on-site installation welding of chemical equipment, if the coating of the electrode does not fall off completely, or the quality of the flux is substandard, and the fluidity and permeability of the slag are poor, it will be difficult to separate from the molten metal to form slag inclusions. If the welding current is too small, the welding speed is too fast, and the temperature of the molten pool is too low, the slag cannot be fully melted and float up and will remain in the weld. Too small a bevel Angle and an improper electrode Angle can both cause slag inclusion defects.

2.4 Incomplete fusion

This intermittent defect occurs when the weld metal and the base metal, and the weld metal and the weld metal do not fully melt and bond during welding, which seriously weakens the strength and integrity of the joint area and may cause serious consequences[2] such as equipment leakage and fracture. The main causes include: (1) the welding speed is too fast, the welding current is too small, and the pool temperature is insufficient, resulting in the base metal or the previous layer of weld metal not being fully melted; (2) Improper Angle of the electrode or torch during the welding operation, where the welding heat is concentrated only on the surface of the weld and fails to penetrate into the base metal or the previous layer of weld; (3) The surface of the base metal is not cleaned properly, and there are impurities such as oil stains, rust, and scale at the bevel, which hinders the bonding of the weld metal to the base metal; (4) In multi-layer welding, if the surface of the weld in the previous layer is not cleaned smooth and there is a defect of unevenness, the heat distribution will be uneven during subsequent welding, which will also lead to incomplete fusion.

2.5 Bite Edge

Undercut is a grooved defect that occurs at the junction of the weld edge and the base metal. This welding defect reduces the effective cross-sectional area of the base metal, causing stress concentration and thereby reducing the strength and fatigue performance of the joint. Especially under high pressure and strong corrosion conditions, undercut can also be the starting point of corrosion, causing crack propagation. This defect is mostly the result of the combined effect of the setting of welding process parameters and improper operation. On the one hand, the welding current is too high, the welding speed is too fast, and the Angle of the electrode or welding torch is improper, causing the base metal at the edge of the weld seam to be over-melted without being filled by the weld metal, resulting in undercut; On the other hand, an improper Angle of the electrode or welding torch, uneven rod movement speed, excessive swing amplitude, too short dwell time of the electrode or welding torch, and a mismatch between the diameter of the electrode or wire and the welding current and speed, resulting in incomplete melting or incomplete filling of the weld edge, can all cause undercut.

3. Prevention and control strategies for welding defects at the installation site of chemical equipment

3.1 Prepare for welding in advance

3.1.1 Material preparation

Based on the actual conditions such as the base material material and operating conditions of the chemical equipment, select welding materials such as electrodes, wires, fluxes, etc. reasonably to ensure that the chemical composition and mechanical properties of the welding materials match those of the base material. Prior to the delivery of welding consumables to the construction site, their production qualification certificates and test reports shall be verified, with sampling inspection implemented to confirm that the welding rods and wires comply with relevant specification requirements. With a focus on the storage of the electrode materials, a special area should be designated to build a welding materials warehouse for the inspected electrodes, and the temperature and humidity of the warehouse environment should be controlled to prevent the electrodes and wires from getting damp and rusting due to the storage environment. Before use, the electrodes should be dried as required to remove moisture and impurities, and then placed in insulated buckets and carried with them to avoid getting damp again. The entire process of storing welding rods is shown in Figure 1. Flux storage should focus on avoiding contamination and caking and be kept[3] properly.

Figure 1 Process for storing welding materials

3.1.2 Equipment preparation

Based on the experience of on-site installation of chemical equipment, various welding processes such as manual arc welding, submerged arc welding, and gas shielded welding are commonly used. Therefore, in the early preparation stage, it is necessary to select the appropriate welding equipment according to the technical requirements of different processes to ensure that the power, current and voltage regulation range of the welding equipment meets the welding requirements. Before the equipment arrives at the site, a comprehensive inspection of the equipment wiring, grounding, and cooling system should be carried out, and parameters such as welding current, voltage, and welding speed should be adjusted to ensure the stability and reliability of the equipment operation. To ensure the implementation effect of the welding process and effectively prevent welding defects, a maintenance system for welding equipment should also be established, with regular cleaning, lubrication, and inspection of the equipment, and timely replacement of damaged parts to avoid equipment failure during the welding process.

3.1.3 Personnel preparation

The technical proficiency and quality awareness of welders are key to controlling on-site welding quality. During the preparation stage, the certification system should be implemented, requiring welders to hold the corresponding welding qualification certificates, be familiar with the base material properties of the equipment being welded and the welding process requirements, and have rich on-site welding experience. Before the welding process is carried out, a specialized training system is established according to different types of welding processes and welding requirements of chemical equipment, with welding process parameters, operation techniques, defect identification and emergency handling measures as the key contents of the training. Practical operation exercises are conducted for the complex working conditions of on-site welding to enhance the operational skills and emergency handling capabilities of welders.

3.2 Strengthen quality control of the welding process

3.2.1 Develop a complete and feasible welding plan

As a guiding document for welding operations at the installation site of chemical equipment, the welding plan should be prepared in accordance with the structural characteristics of the chemical equipment, the material of the base material, the working conditions and the on-site conditions, and should be complete and feasible. In the welding plan, clear requirements should be made for different welding process parameters, welding operations, bevel design, welding sequence, etc., and in combination with welding safety and quality issues, contents such as quality control points and emergency handling measures should be improved. For example, for manual arc welding, emphasis should be placed on electrode drying, residual heat and current control in the welding plan to prevent porosity defects. After the plan is completed, professional technicians should be organized to review it, and timely adjustments should be made in accordance with the dynamic changes of the on-site conditions to ensure that the welding plan is always highly consistent with the on-site welding requirements.

3.2.2 Welding power supply and polarity and process parameter control

In accordance with the specification requirements of the welding scheme, during the welding operation of the on-site installation of the chemical equipment, a suitable welding power source and polarity should be selected first based on the welding method and welding material. As an example, direct current reverse polarity or alternating current power is adopted for shielded metal arc welding (SMAW), while direct current straight or reverse polarity is applied for gas-shielded welding. Such configurations stabilize the welding arc and facilitate sound weld formation. Meanwhile, critical process parameters including welding speed, welding current and arc voltage must be rigorously controlled to prevent inadequate weld strength from excessive travel speed and weld filler overmelting caused by overhigh current or voltage. In multi-layer welding, the control of interlayer temperature should be the top priority to avoid too high or too low interlayer temperature, and ensure that the previous layer weld is fully cooled before proceeding to the next layer to prevent defects such as cracks and slag inclusions. On this basis, preheating temperature and holding duration shall be implemented in accordance with the requirements specified in the welding procedure to homogenize the temperature of base metal and weld metal and mitigate stress concentration. In the entire welding process, real-time parameter monitoring should be used as an important link to control welding quality. Relying on advanced sensors and data acquisition systems, dynamic monitoring should be carried out around key welding parameters. Once abnormal parameters or sharp fluctuations are detected, personnel should be alerted in a timely manner to make adjustments, providing data support for the prevention and control of welding defects.

3.2.3 Quality Traceability of the welding process

Focus on the technical operations of the on-site installation welding process of chemical equipment and establish a quality traceability system for the welding process. First, clearly define the traceability content and record in detail in the system the batch, specification, inspection report of the welding material, the model and operating status of the welding equipment, the name and qualification certificate number of the welder, the welding process parameters, the welding time, the welding position, as well as the abnormal conditions and handling measures during the welding process. Secondly, assign a dedicated person to record the welding process, strictly prohibit random alterations, and ensure the authenticity, accuracy, and completeness of the information recorded. Test results shall be periodically sorted and archived to underpin subsequent quality inspection and welding defect analysis. Finally, strengthen on-site supervision and management, arrange for quality management personnel to conduct on-site inspections, focusing on verifying whether welding operations comply with process requirements, whether records are complete, and promptly identify and correct violations.

3.3 Implement post-weld quality inspection and analysis

3.3.1 Visual inspection

After the welding operation is completed, when the weld seam cools to room temperature, visual inspection can be carried out promptly, using a combination of visual inspection and magnifying glass inspection, with a focus on the following: (1) whether the surface of the weld seam is smooth, continuous, free of cracks, pores, slag inclusions, incomplete fusion, undercut and other defects; (2) Whether the width, height and excess height of the weld are in accordance with the design requirements, and whether the bevel Angle and gap are uniform; (3) The transition between the weld seam and the base metal is smooth without obvious changes; (4) Whether there are impurities such as oil stains, rust, and oxide scale on the surface of the welded joint.

3.3.2 Physical and chemical properties testing

In order to further assess the internal quality of the welded joint, in the prevention and control of welding defects, abstract inspection of the welded joint area should be carried out according to the importance of the chemical equipment and the operating conditions. In physical property testing, various methods such as tensile tests, impact tests, hardness tests, and bending tests are used to test the tensile strength, impact toughness, hardness, plasticity and other mechanical properties of the welded joint to determine whether the quality of the welded joint meets the relevant standard requirements. In chemical performance tests, chemical composition analysis of the welded joints is mainly conducted to determine whether the content of metal elements in the weld seam complies with the design specifications. Especially for chemical equipment used in high-temperature, high-pressure, and highly corrosive conditions, corrosion resistance tests are also required to ensure that the welded joints can adapt to the actual working environment[4].

3.3.3 Non-destructive testing

Taking into account the possible welding defects that may be formed in the on-site installation welding of chemical equipment due to various factors, after the welding is completed, non-destructive testing methods such as ultrasonic testing, radiographic testing, magnetic particle testing, penetrant testing, etc. can be reasonably selected according to the structural characteristics of the equipment, defect types and relevant standards to accurately detect welding defects without damaging the welding joints. Determine the location, size and shape of the defects to provide a basis for subsequent rework.

3.4 Standardize the repair of welding defects on the ground

For welding defects detected in the quality inspection process, it is necessary to first determine the type, size, location of the defect and the operating conditions of the chemical equipment, then formulate a reasonable rework plan, clearly define the rework process parameters, methods, frequency and quality requirements, and implement it only after it has been reviewed and approved by professional technicians. In the standard rework operation, the defect should be thoroughly removed first, beyond the edge of the defect itself, and the repair welding should be carried out after confirming that there is no residual defect. The identical welding consumables and welding procedures as the original weld shall be adopted, and relevant process parameters shall be rigorously controlled. This ensures favorable metallurgical bonding between the repaired weld, original weld and base metal and prevents new defects arising from improper operational practices.

4. Conclusion

To sum up, the formation of welding defects in the on-site installation of chemical equipment involves multiple factors such as materials, equipment, personnel, environment, and process. In its prevention and control, a systematic prevention and control system of people, machines, materials, methods, and environment should be constructed around the entire welding process to effectively reduce the possibility of welding defects, and the defects that have already occurred should be repaired. With the development of modern digital technology, intelligent means can be attempted in the future to improve the level of welding defect prevention and control.

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