High Temperature Corrosion Protection of Heating Surface Metals of Waste Incineration Power Generation Boilers: A Review

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Abstract. Waste incineration power generation technology is the main trend in the treatment of urban solid waste. The thermal corrosion protection of boiler water-cooled walls and superheater tube walls is a key issue that restricts the stable operation of garbage incinerators. This article outlines typical surface protection technologies in the field of boiler high-temperature corrosion protection, including hardfacing, thermal spraying, remelting, etc. In addition, the characteristics of these anti-corrosion technologies were evaluated, and their application prospects were prospected. Hardfacing is widely used, but it is also facing the challenge of other methods; among the commonly used thermal spraying technologies, supersonic flame spraying is a more reliable technical solution; in laser remelting, high frequency induction remelting, flame remelting Among various remelting technologies such as melting and integral heating remelting, high-frequency induction remelting has shown great development potential.

Keywords: Garbage Incineration, Thermal Corrosion, Surface Protection, Thermal Spraying

1. Introduction
As an efficient, clean and resource-based waste treatment method, waste incineration power generation is favored by all countries in the world. As of 2018, the daily processing capacity of global waste incineration plants has reached 700,000 t d⁻¹ [1]. However, the problem of corrosion has always been an important reason hindering the development of waste incineration power generation. Since metal parts such as water wall, superheater, heat exchanger, induced draft fan are eroded by medium and high temperature flue gas during the operation of the boiler, the material will continue to peel and thin. This not only increases the high costs for the enterprises concerned, but also makes it impossible to guarantee the safety of the boiler operation. The high-temperature corrosion of these heated surfaces
usually includes oxidative corrosion, thermal corrosion, chloride corrosion, etc. Among them, chloride corrosion is the main one. This paper reviews the anti-corrosion technologies commonly used in the heating surface of waste incineration boilers, such as hardfacing, thermal spraying, and remelting, analyzes the advantages and disadvantages of these technologies, and prospects their application prospects.

2. Hardfacing Technology
The hardfacing technology has been adopted and used since the 1990s, and it has shown good protection effects in the early application of the water wall of the waste incinerator and some superheaters. Commonly used hardfacing methods include molten electrode inert gas shielded welding (MIG), molten electrode active gas shielded arc welding (MAG), cold metal transition technology (CMT), etc.

![Figure 1](image)

**Figure 1.** The equipment used for MIG welding [1].

As shown in Figure 1, MIG is an arc welding method that uses a melting electrode, an external gas as an arc medium, and protects the metal droplets, welding pool, and high-temperature metal in the welding zone. Sun et al. [2] used MIG surfacing technology to surface Inconel 625 alloy on the surface of the water wall, and studied the structure and performance of the water wall. The results show that the surfacing layer forms a dense metallurgical bond with the 20G substrate, the surfacing layer has a higher hardness than the substrate and has good toughness. MAG is a kind of mixed gas shielded welding in which a small amount of oxidizing gas (oxygen, carbon dioxide or its mixed gas) is added to argon. The process is similar to MIG. CMT welding promotes the droplet transition through the wire drawing movement, the short circuit current is very low, and the entire welding process is a high-frequency "hot-cold-hot" conversion process, which can greatly reduce the heat generation. Qiu et al. [3] believe that using the CMT welding system to overlay a layer of high-temperature corrosion-resistant Inconel 625 alloy on the heating surface of the boiler can effectively solve the corrosion problem of the heating surface tube. Fan [4] compared the Inconel 625 alloy with CMT technology and the carbon steel substrate, and found that the expansion coefficients of the two are small, and it is not easy to crack when used.

Compared with thermal spray coating technology, the surfacing cladding layer can form a strong metallurgical bond with the substrate, the structure is more uniform, and the thickness can reach a few centimeters. Under appropriate conditions of use, its performance stability and long-lasting protective effect have obvious advantages. But there are also the following problems: high dilution rate, deep bath, thick coating, can not adapt to excessive temperature. In addition, alloy materials for surfacing applications have low hardness, are not wear-resistant, and have low production efficiency. At the same time, in-situ repair is also an insurmountable problem for surfacing technology. It is easy to cause embrittlement of the original cladding layer during the secondary surfacing repair, and the
cracks will propagate to the substrate and cause overall failure [5].

3. Thermal Spraying
In recent years, the research and application of thermal spraying technology in garbage incinerators has become a hot spot, and it is also considered to be one of the more effective and appropriate technical means to solve the problem of heat exhaust corrosion of water-cooled wall pipes. Among them, supersonic flame spraying, plasma spraying, and arc spraying are several representative technical solutions.

3.1 Supersonic Flame Spraying
Supersonic flame spraying (HVOF) has the characteristics of relatively low flame temperature and fast particle flight speed. It has obvious technical advantages in the preparation of metal alloys and cermet coatings with high density and low oxygen content. The working principle is that after the powder is heated and melted, it hits the substrate surface at high speed to form a coating. Due to the high combustion speed of the gas flame stream in this spraying method, supersonic powder particles can be obtained, and the kinetic energy of impact on the substrate is large, so the bonding strength of the coating and the substrate and the density of the coating are improved. Oksa et al. [6] sprayed several high-chromium thermal spray coatings with HVOF technology and tested their corrosion resistance. As shown in Figure 2, these coatings generally have good corrosion resistance at high temperatures.

![Figure 2. The maximum thickness of the oxide/corrosion layer formed during the test (μm) [6].](image)

Although supersonic flame spraying is more outstanding in terms of coating performance, its process cost is expensive, including large equipment investment, frequent replacement of worn parts, amazing gas consumption, high powder quality requirements, and low coating deposition rate. This limits its further promotion in actual use, especially in the domestic market where the cost is more demanding. Therefore, the search for suitable alternative technologies is also one of the trends in the development of thermal corrosion protection for pipe walls of garbage incinerators.

3.2 Plasma Spray
Plasma spraying has the advantages of high beam temperature, good coating quality, and wide material adaptability. It can prepare a variety of coatings such as metals, alloys, ceramics and composite materials. Guo [7] conducted an experimental study on the plasma sprayed NiCr and Cr$_7$C$_2$-NiCr coatings for the protection of garbage boiler pipes. The results show that the two coatings prepared by plasma spraying have a layered structure, the phase of the coating and the spray powder composition is basically consistent. Shi [8] et al. studied the mechanical properties of plasma sprayed nano-alumina-titanium coatings. The results show that the nano-ceramic coatings have high bonding strength and hardness, and the nanostructure of the original powder can be maintained in the coating.

Studies on the structure and thermal corrosion behavior of plasma sprayed coatings show that its performance is similar to that of supersonic flame sprayed coatings, and it can play an effective and stable protective role on the tube wall of heat exchange components of garbage incinerators. However,
this technology also faces problems such as expensive equipment, high energy consumption, and complex processes. Therefore, the plasma spraying technology is still mainly researched on the thermal corrosion of the tube wall of the waste incinerator, and has not been widely applied in practice.

3.3 Arc Spraying
With its simple equipment, flexible operation, high deposition efficiency, and low cost, arc spraying has become one of the most suitable spraying methods for large-scale construction on site. The arc-sprayed NiCrB powder core wire developed by Wang [5] et al., although the Cr content of the prepared coating (25%-30%) is lower than that of NiCrTi coating (Cr: 43%-45%), the oxide The reduction significantly improves its thermal corrosion resistance under similar garbage incinerator operating conditions, as shown in Figure 3. Xu et al. [9] addressed the problem of high-temperature chlorine corrosion and erosion wear on the heating surface of waste incineration boiler pipes. A nickel-based alloy C276 coating was prepared on the heating surface by high-speed arc spraying to test its corrosion behavior. The results show that the coating has excellent electrochemical performance against molten salt ions and high temperature chlorine corrosion resistance.

![Figure 3. Thermo-gravimetric curves of the coatings and substrate subject to hot corrosion in NaCl environment at 800 °C](image)

Compared with other spraying methods, arc spraying coatings have high porosity and oxide content. At the same time subject to the wire drawing process, its coating alloy composition adjustment space is relatively small. As a result, the application of arc spraying technology in garbage incinerators with more severe corrosive environments has been greatly restricted. In recent years, by adding an appropriate amount of "deoxidation" elements to the wire, the formation of sprayed oxides can be significantly reduced, and the ability of the coating to resist thermal corrosion can be effectively improved [10].

4. Remelting Technology
Remelting is the process of melting the coating on the workpiece again. Remelting technologies include laser remelting, induction remelting, flame remelting, and overall heating remelting. For the coating of the water wall of the waste incineration power generation boiler and the superheater, considering the quality of the remelting and the process stability, efficiency and cost, the most suitable ones are laser remelting, flame remelting and high frequency induction remelting. Kinds of ways.

4.1 Laser Remelting Technology
Laser remelting is to melt the surface with a laser beam without adding any metal elements in the process, so as to achieve the purpose of improving the surface structure. Sheng [11] used laser technology to remelt the high-speed arc sprayed FeNiCrAl coating, and analyzed the structure and profile of the coating before and after remelting. The results show that after remelting, the layered stacking structure and pores of the sprayed layer are eliminated, the organizational structure becomes
uniform and dense, and the coating and the substrate change from mechanical to metallurgical.

The advantage of laser remelting is that it has high energy density, which can remelt materials with high melting points, and because the diameter of the spot can be adjusted, the controllability is good, and it is suitable for remelting and requiring higher precision parts. The disadvantage is that the rapid heating and cooling process in the laser remelting process makes the coating prone to cracks, and the gas in the molten pool is also not easy to exhaust to form pore defects. Therefore, cracks, holes and spalling are the main existing in laser remelting problem.

4.2 Flame Remelting Technology
Flame remelting is a method that uses a flame such as oxyacetylene to heat the sprayed layer, melt it, and then cool and solidify to improve the performance of the sprayed layer. Compared with other remelting methods, the flame remelting heat source temperature is lower, so it is suitable for remelting alloy coatings. Dong et al. [12] prepared a plasma arc sprayed NiCrBSi+w (WC) 15% coating and performed flame remelting treatment. After remelting, the microstructure of the coating has been significantly improved, cracks, pores, and unmelted particles have been reduced, the grains have been refined, the hardness of the coating has reached HV800, and the wear performance has been significantly improved. The flame remelting equipment is simple, easy to operate, and easy to operate on the construction site, but because it is difficult to accurately control the heating depth and achieve uniform heating, it is necessary to strictly control the speed of the flame gun and the distance from the workpiece.

4.3 High Frequency Induction Remelting
High-frequency induction remelting refers to the use of high-frequency induction to heat and melt the coating using the induced current (eddy current) generated in the workpiece and coating. Compared with laser remelting, high-frequency induction remelting technology requires less equipment, simple process, and low cost. It is more suitable for the mass production of more regularly shaped products such as water-cooled wall pipe rows. In recent years, many scholars have done a lot of research on the bonding mechanism, the influencing factors of cladding parameters and the remelting mode in the process of induction cladding. In recent years, the United States, the United Kingdom, Japan and other countries have applied more and more self-fluxing alloy (NiCrSiB) coatings on the water-cooled walls of waste incineration boilers using high-frequency induction heating [13]. As shown in Figure 4, Valean [14] et al. sprayed a NiCrBSi coating on the surface of the substrate through an oxygen-acetylene flame, and then applied the high-frequency induction remelting technique to melt the coating again. After remelting, the porosity of the coating decreased from an initial value of approximately 15% to a final value of less than 3%, and both the wear rate and corrosion behavior were improved. In addition, as shown in Figure 5, induction remelting has a higher microhardness than flame remelting.

![Figure 4. Inductive remelting process](image1)

![Figure 5. Microhardness values obtained for flame remelting](image2)
of the NiCrBSi coating [14]. and electromagnetic remelted NiCrBSi coatings [14].

In general, the advantages of induction remelting are outstanding: high degree of automation, avoiding human factors; achieving micro-metallurgical bonding, low dilution rate, high bonding strength; high efficiency, safety and environmental protection; strict control of coating quality and composition, and high pass rate; The cost is lower than the surfacing; the thermal deformation is small, which is conducive to assembly.

5. Conclusion
(1) The surfacing technology is currently widely used and has achieved good results, but due to its high cost, high dilution rate, and low efficiency, it is being challenged by other methods.

(2) Despite the early origin of thermal spraying technology, in the practice of protective treatment of the water-cooled wall surface of garbage incinerators, the effect is not very ideal due to factors such as coating thickness design, pretreatment and spraying construction technology. Among several commonly used thermal spraying technologies, supersonic flame spraying is a more reliable technical solution.

(3) The rapid development of remelting technology in recent years, but in the specific implementation, the appropriate method should be selected according to the different characteristics and application scope of various remelting processes. For the preparation of water-cooled wall coatings for waste incineration boilers, high-frequency induction remelting has shown great development potential in improving the structure and performance of thermal spray coatings.

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References
[1] Zhan X H, Li Y B, Qu W M et al. . Comparison between hybrid laser-MIG welding and MIG welding for the invar36 alloy. Optics & Laser Technology. 2016, 85, 75-84.
[2] Sun H H, Liu A G, Meng F L. Microstructure and Properties of Boiler Membrane Water-Cooled Wall of Inconel625 Alloy Surfacing. Journal of Materials and Heat Treatment. 2013,34 (S2), 96-99 (in Chinese).
[3] Qiu L L, Bian H J. Technical Analysis of Inconel 625 Nickel-based Materials for CMT Surfacing of Boiler Heating Plant Boiler Heating Surface. Science and Technology Innovation. 2018, 18, 162-163 (in Chinese).
[4] Fan H P. Technical Analysis of Water-cooled Film Wall Surfacing Welding Superalloys in Waste Incinerator. Henan Science and Technology. 2018, 08, 25-26 (in Chinese).
[5] Wang L, Zhou Z, Wang G H et al. . Surface Protection Technology for Thermal Corrosion of Waste Incinerator. Thermal Spray Technology, 2017, 9 (01), 1-6 (in Chinese).
[6] Oksa M, Tuurma S, Varis T. Increased Lifetime for Biomass and Waste to Energy Power Plant Boilers with HVOF Coatings: High Temperature Corrosion Testing Under Chlorine-Containing Molten Salt. Journal of Thermal Spray Technology. 2013, 22(5), 783-796.
[7] Gou P. Plasma sprayed NiCr and Cr3C2-NiCr coatings for boiler pipeline protection and characterization of mechanical properties. Chemical Engineering and Equipment. 2018, 12, 32-36+62 (in Chinese).
[8] Shi X Z, Xu K W, Wu X Y. Mechanical Properties of Plasma Sprayed Nano-alumina Titanium Coating[J]. Surface Technology, 2018, 47 (04), 96-101 (in Chinese).
[9] Xu L, Tan W, Zhu Q X, Lu Q Q et al. . Research on High Temperature Chlorine Corrosion Resistant Nickel-Based Arc Coating Applied to Waste Incinerator. Materials Protection.
[10] Zhou Z, He D Y, Zhao X Z, et al. Wear and high-temperature corrosion behavior of a wire-arc sprayed Ni Cr B coating. Thermal Spray Bulletin, 2013, 6(1), 48-54 (in Chinese).

[11] Sheng Z Q, Zhou J, Hu L, Wei S Z. Microstructure and Fracture Toughness of Laser Remelting High Speed Arc Sprayed FeNiCrAl Coating. Journal of Northeastern University (Natural Science). 2018, 39 (04), 506-510 + 521 (in Chinese).

[12] Dong X Q, Wang Y Q, Zhang N N, Cai H. Effect of flame remelting on microstructure and properties of nickel-based tungsten carbide coatings. Hot Working Technology. 2013, 42 (12), 154-157 (in Chinese).

[13] Galetz M C, Bauer J T, Schütze M, et al. Resistance of coatings for boiler components of waste-to-energy plants to salt melts containing copper compounds. Journal of Thermal Spray Technology, 2013, 22(5), 828-837.

[14] Zhan X H, Li Y B, Qu W M et al. Comparison between hybrid laser-MIG welding and MIG welding for the invar36 alloy. Optics & Laser Technology. 2016, 85, 75-84.