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# MICROWAVE STATIC CALCINATION FOR REMOVAL OF HIGH CHLORINE FROM HOT-DIP GALVANIZING ASH FOR PREPARING CERAMIC GLAZE-GRADE ZINC OXIDE

In view of the practical challenges in industrial dechlorination production of hot-dip galvanizing ash with dynamic roasting in rotary kilns, the static microwave calcination dechlorination was firstly proposed. The effects of calcination temperature, holding time and heating power were systematically researched in this study. The calcination temperature of 900°C, holding time of 60 min and heating power of 70% (560 W) were identified as the best technical parameters. At the optimum conditions, the content of chlorine in the product was reduced from 11.59% to 0.13% and the dechlorination efficiency reached 99.28%. The energy-economic assessment was conducted revealing that processing the high chlorine hot-dip galvanizing ash with a microwave muffle furnace saving 2,107 CNY per ton compared to the rotary kiln.

*Keywords:* Hot-dip galvanizing ash; Microwave calcination; Zinc recovery; Dechlorination; Ceramic glaze-grade zinc oxide

## 1. Introduction

Hot-dip galvanizing is currently the most fundamental, widely used and effective anti-corrosion method for protecting steel materials worldwide. It plays an irreplaceable role in corrosion reduction, lifespan extension, energy conservation and material savings for steel materials, with approximately 50% of global zinc consumption being used for hot-dip galvanizing [1-3].

During the hot-dip galvanizing process, the surface of molten zinc bath is exposed to air and oxidizes. Additionally, some fluxing agents enter the galvanizing bath and react with molten zinc to form dross, which is primarily composed of zinc oxide, metallic zinc, and chlorides, and typically containing 50% to 80% zinc by mass, along with minor impurities such as Fe, Pb, Al and Cl, and it reduces the utilization efficiency of zinc [1,4].

In current industrial hot-dip galvanizing production, most of the metallic zinc in the dross is recovered and then returned to hot-dip galvanizing process through ball milling and sieving, which also results in the hot-dip galvanizing ash. Thus, hot-dip galvanizing ash is a by-product of the galvanizing process and represents an important secondary zinc resource [5,6]. According to the National Catalog of Hazardous Wastes (2021 Edition), hot-dip galvanizing ash is classified as a hazardous solid waste (code: HW23-003). Therefore, recycling the hot-dip galvanizing ash is a sustainable approach to convert waste into valuable resources, which is of great significance for societal sustainability.

Currently, pyrometallurgical and hydrometallurgical processes are usually employed for treating such secondaries zinc-bearing materials both domestically and internationally [7-9]. Pyrometallurgical methods primarily include liquation smelting, distillation and vacuum distillation, with the final products mainly being zinc powder and metallic zinc ingots [10-13]. Hydrometallurgical methods mainly involve chemical processes and electrolysis, yielding chemical products such as zinc oxide, zinc sulfate, zinc carbonate hydroxide and other zinc salts [14-16]. However, both pyrometallurgical and hydrometallurgical processes have certain drawbacks. The pyrometallurgical process requires high energy consumption and equipment costs. While the hydrometallurgical process often involves multiple processing steps and requires large quantities of chemical reagents, resulting in higher production costs. In summary, the current existing methods for recycling secondary zinc-bearing materials into zinc metal or zinc compounds have certain limitations, making it particularly important to explore new application pathways for the hot-dip galvanizing ash.

As we know, Grade 0 zinc ingots are usually used as the raw material in hot-dip galvanizing production, resulting in ex-

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tremely low content of harmful heavy metal elements such as lead and cadmium in the zinc ash. So the hot-dip galvanizing ash is primarily a mixture of crude zinc oxide and varying quantities of various other contaminants (e.g. Al, Fe, Pb, and Cl). The Fe impurity mainly comes from galvanized steel parts but the content is very small. The Al impurity mainly comes from essential process additives in hot-dip galvanization and is oxidized to aluminum oxide which is a beneficial component for ceramic glaze-grade zinc oxide. On the contrary, $Al_2O_3$ is a highly detrimental impurity in metallic zinc products. The Cl impurity mainly comes from the use of chloride fluxes in the galvanizing process and which is a very harmful element for ceramic glaze-grade zinc oxide. Based on the physicochemical characteristics of hot-dip galvanizing ash, Li proposed an innovative approach for the high-efficiency utilization of hot-dip galvanizing ash to prepare ceramic glaze-grade zinc oxide, as first disclosed in his patent [17]. The process has achieved commercial-scale production. The company currently adopts the following procedure to comprehensively recycle hot-dip galvanizing ash: iron removal-rotary kiln roasting for dechlorination (at approximately 1200-1300°C)-ball milling for refinement-air classification for further iron removal-production of the final qualified ceramic glaze-grade zinc oxide product. However, this process currently faces several challenges. First, rotary kiln roasting is a dynamic process, causing some zinc oxide to be lost in the dust collection system and reducing zinc recovery. Second, the process suffers from high energy consumption, inefficient dechlorination, low zinc recovery, and high production costs. Moreover, the dependence on conventional carbon-based fuels in rotary kiln operations results in significant $CO_2$ emissions, which is increasingly incompatible with the strategic objectives of China's dual-carbon policy. To overcome these limitations, this work introduces an innovative static microwave calcination process for dechlorination, offering a more efficient and environmentally friendly alternative. Currently, the primary dechlorination methods include water washing [18], alkali washing [19], high-temperature oxidative [20], and microwave stirring roasting [21-23]. Water washing dechlorination suffers from low efficiency, and the material after washing still exhibits a high chlorine content. The alkali washing dechlorination process consumes sodium carbonate and steam, along with producing substantial wastewater, which substantially elevates operational costs for the enterprise. High-temperature oxidative dechlorination, typically carried out in multiple-hearth furnaces or rotary kilns, suffers from significant drawbacks such as high equipment investment and substantial energy consumption. The microwave stirring roasting technology was developed by Peng Jinhui group in Kunming University of Science and Technology [21-23]. This method offers the advantages of low dechlorination temperature (reduce the heating temperature of 200-300°C), rapid heating rate, and high dechlorination efficiency, and so on. However, an increase in the stirring rate leads to enhanced dust entrainment in the off-gas. This not only reduces the direct recovery efficiency of zinc but also raises the risk of pipeline blockage. In summary, all existing dechlorination processes have certain limitations or drawbacks. Based on other researchers' previous research, this study proposes a microwave static dechlorination process. The equipment and the dechlorination principle are completely different from those of microwave stirring roasting.

## 2. Experimental

### 2.1. Materials

In the process of hot-dip galvanizing steel pipes, the resulting zinc ash (commonly known as pipe ash in the industry) contains a high chlorine content of 10%-20%. A representative sample of hot-dip galvanized pipe zinc ash collected in an industrial galvanizing plant in Tianjin city which ground and screened to remove metallic zinc firstly was used as the raw material in this study. The main element composition of the hot-dip galvanizing ash is given in TABLE 1. The content of Zn, Cl, Fe, and Pb are 55.62%, 11.59%, 0.41% and 0.35%, respectively. It is evident that the chlorine content in the experimental raw material significantly exceeds levels reported for other chlorine-bearing materials, such as zinc oxide dust, zinc ash, zinc dross, electric arc furnace flue dust, brass smelting automobile scrap and sludge.

TABLE 1

Chemical composition of the hot-dip galvanizing ash

| **Element** | **Zn** | **Cl** | **Fe** | **Pb** |
|---|---|---|---|---|
| wt.% | 55.62 | 11.59 | 0.41 | 0.35 |

The phase composition of the zinc ash was analyzed using X-ray diffraction using Cu Kα radiation in the range of 10°-80° (2θ) (XRD, PANalytical, X'Pert Powder). The XRD pattern of the hot-dip galvanizing ash was shown in Fig. 1. As shown in Fig. 1, the composition of the hot-dip galvanizing ash is relatively complex, and its main phases are ZnO, $Al_2O_3$, $Fe_2O_3$, $PbCl_2$

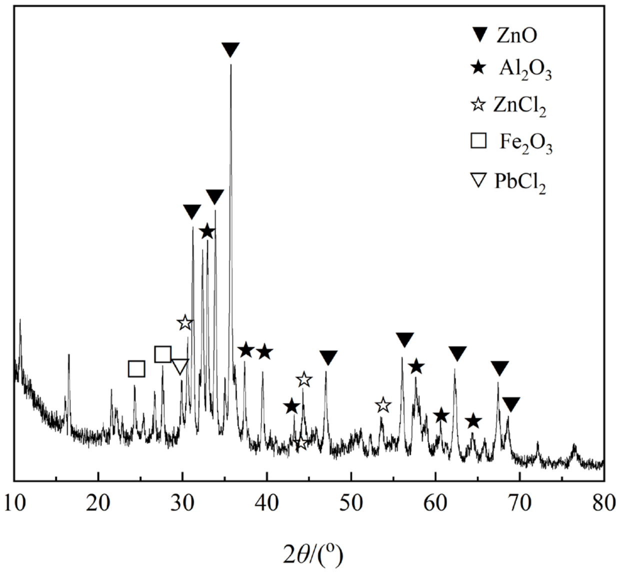

Fig. 1. The XRD pattern of the hot-dip galvanizing ash

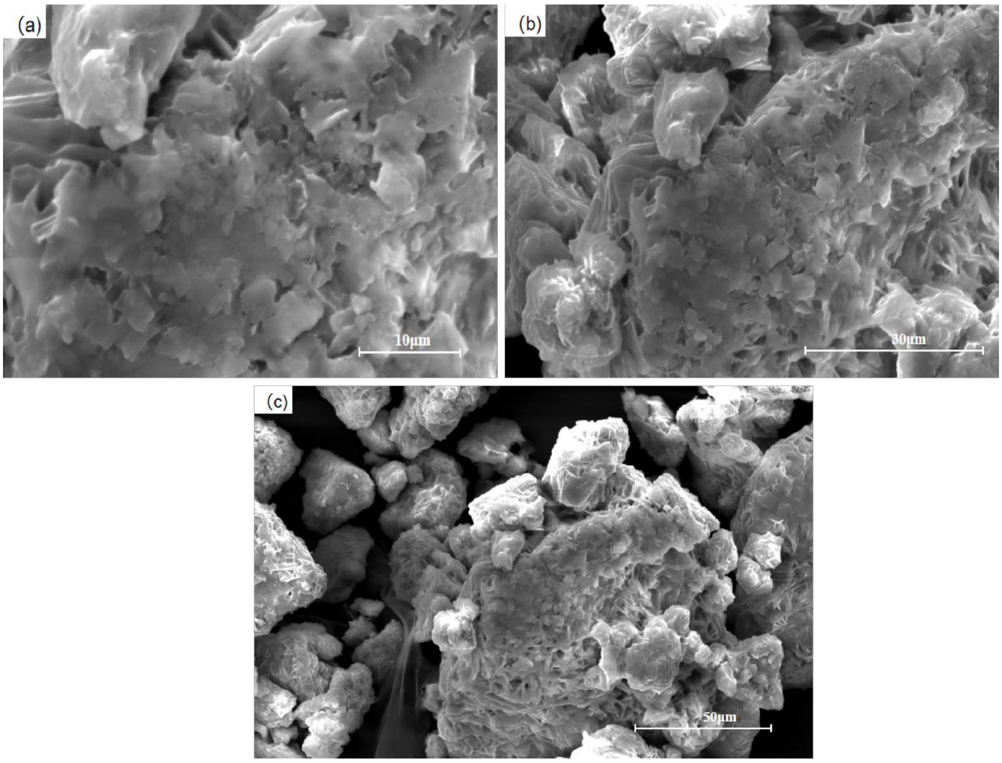

Fig. 2. The SEM image of the hot-dip galvanizing ash

and $ZnCl_2$. It can be seen that chlorine exists primarily in the form of zinc chloride and a small amount of lead chloride. The morphology of the ash was observed using a scanning electron microscope( SEM, FEI Quanta FEG 250). As shown in Fig. 2, particles with sizes ranging from approximately 10 to 500 µm were characterized with a rough surface and a dense microstructure, with no observable surface porosity.

### 2.2. Experimental equipment

The experiments were conducted using a microwave muffle furnace (MKX-M1B, Qingdao Microwave Creative Technology Co., Ltd.) with a maximum heating power of 0.8 kW. To minimize experimental contamination and facilitate by-product recovery, a small-scale fabric filter system (WNHB-Mc, Jinan Weimin Environmental Protection Equipment Co., Ltd.) was employed. A schematic diagram of the experimental setup is presented in Fig. 3.

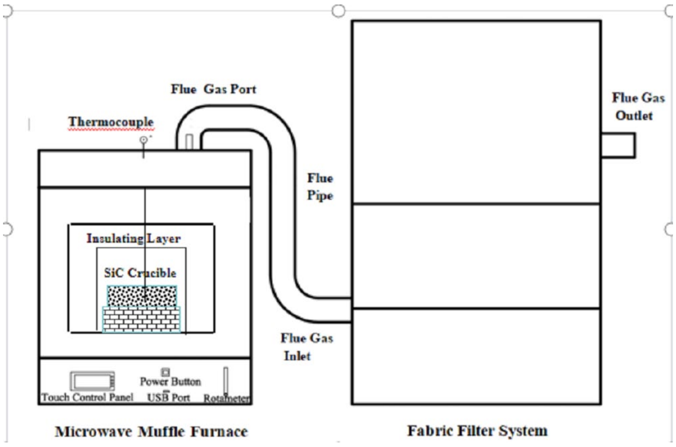

Fig. 3. Schematic diagram of the experimental setup

### 2.3. Experimental principle

As shown in Fig. 1, the chlorine in hot-dip galvanizing ash primarily exists in the form of $ZnCl_2$. Basing on the distinct microwave absorption properties of zinc compounds, $ZnCl_2$ exhibits strong microwave absorption while ZnO absorbs microwaves weakly, so microwave irradiation can be utilized for selective heating to achieve efficient chlorine removal [24-26]. Moreover, Zinc chloride has a relatively low melting point of 318°C and boiling point of 732°C, respectively. Given the oxygen-limited atmosphere inside a microwave muffle furnace, it can be inferred that the primary mechanism for chlorine removal during microwave calcination of hot-dip galvanizing ash is the volatilization of $ZnCl_2$ as shown in formula (2.1).

$$ZnCl_2 \triangleq ZnCl_2(g) \tag{2.1}$$

### 2.4. The specific heat capacity measurement

For the energy consumption and economic evaluation of this experiment, the specific heat capacity of the raw material needs to be determined. The specific heat capacity of the hot-dip galvanizing ash was measured using classic mixing calorimetry technique. Basing on the law of energy conservation, the specific heat capacity of hot-dip galvanizing ash was calculated by establishing that all heat released from the hot-dip galvanizing ash was absorbed by water.

### 2.5. Experimental procedure

200 g of hot-dip galvanizing ash was precisely weighed using a YP1001B electronic balance (accurate to 0.1 g) and then placed into a dedicated silicon carbide crucible. The crucible was then transferred into the microwave muffle furnace, the thermal barrier was installed, and the furnace door was closed. The relevant experimental parameters, including heating temperature, holding time and microwave power) were set. The microwave system and the fabric filter system were then started to begin the experiment. After the microwave muffle furnace program completed, the silicon carbide crucible was removed and weighed. The experimental data were recorded, and the calcination products were ground and stored in pre-labeled, moisture-proof bags. Finally, the volatile products were collected from the filter bag.

### 2.6. Element determination

To ensure the accuracy of experimental data, the element composition of both of the raw materials and the products were sent to the original supplier for testing and analysis. The chlorine content was determined using the Volhard method. Elements zinc and lead were determined by the EDTA titration method, and element iron was determined by the cerium sulfate titration method.

## 3. Results and discussion

### 3.2. The specific heat capacity of the hot-dip galvanizing ash

The specific heat capacity of the hot-dip galvanizing ash was carried out using the mixing calorimetry technique (BRR-3B, Hunan Zhenhua Analysis Instrument Co., Ltd.). The specific heat capacity of the raw material was determined through triplicate parallel measurements, with the mean value adopted as the final result which is demonstrated in TABLE 2. As shown in TABLE 2, the specific heat capacity of the hot-dip galvanizing ash is 2350.86 J/(kg·°C). The value demonstrates that the material possesses a relatively high specific heat capacity. The traditional rotary kiln heating process relies primarily on conductive heat transfer, which requires heating the entire bulk of material. Due to the high specific heat capacity of hot-dip galvanizing ash, a substantial amount of heat energy is required, leading to high energy consumption in industrial dechlorination operations.

TABLE 2

The specific heat capacity of the hot-dip galvanizing ash

| **Measurement repetitions** | **1#** | **2#** | **3#** | **The average** |
|---|---|---|---|---|
| The specific heat capacity/[J/(kg·°C)] | 2363.06 | 2332.53 | 2356.98 | 2350.86 |

### 3.3. The heating performance of hot-dip galvanizing ash in a microwave field

200 g of the hot-dip galvanizing ash was heated with 100% heating power, the heating rate curve of the hot-dip galvanizing ash was shown in Fig. 4. As shown in Fig. 4, the raw material exhibits good microwave absorption properties. And the heating rate decreases with prolonged heating time demonstrating the selective heating characteristics of microwaves. During microwave irradiation, the microwave energy is effectively absorbed, leading to rapid heating of the ash, which can reach approximately 900°C within 47 min.

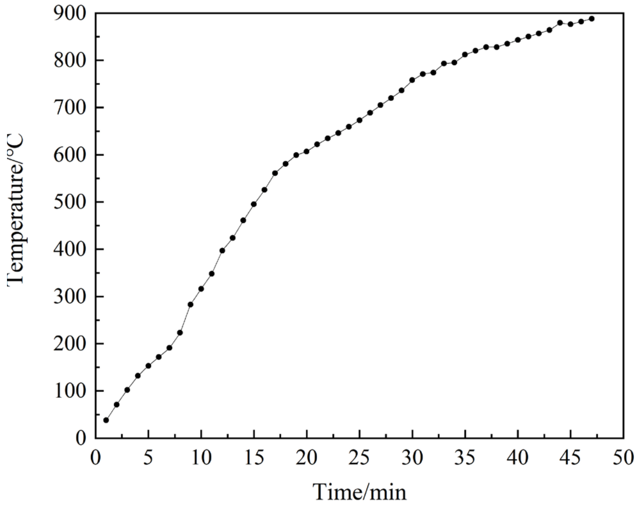

Fig. 4. The heating rate curve of the hot-dip galvanizing ash

### 3.4. Effect of calcination temperature on chlorine removal

The influence of calcination temperature on dechlorination efficiency was investigated over a range of 600 to 1000°C. Experimental conditions were shown as follows: the mass of experimental raw material was 200 g, the heating power was 70%, the holding time was 60 min. The dechlorination rates and chlorine content in the calcination products as a function of calcination temperature are presented in Fig. 5. As shown, the dechlorination rate increases while the chlorine content decreases with increasing calcination temperature. The dechlorination rates are both more than 99% with the temperature increasing up to 900°C and 1000°C, respectively. At the same time, the content of chlorine in calcination products are 0.13% and 0.027%, respectively. Considering both energy consumption and the chlorine content requirements of ceramic glaze-grade zinc oxide, a calcination temperature of 900°C was identified as the optimal condition.

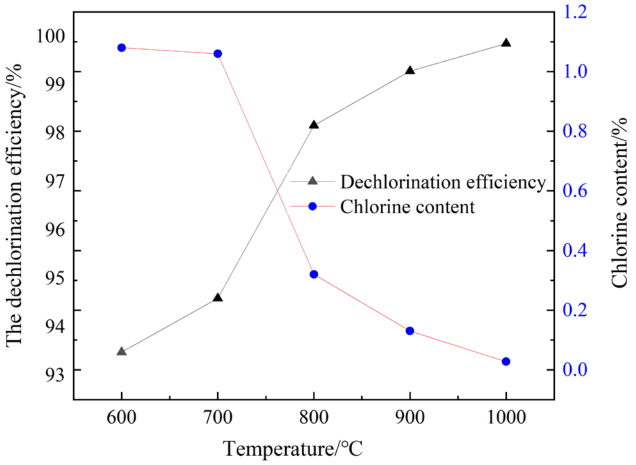

Fig. 5. The dechlorination rates and chlorine content in the calcination products as a function of calcination temperature

### 3.5. Effect of holding time on chlorine removal

The content of chlorine in calcination products and dechlorination rate were studied within a holding time range of 30-150 min. The experimental conditions were as follows: the experimental raw material mass of 200 g, the calcination temperature of 900°C and the heating power of 70%. Fig. 6 presents the chlorine removal and chlorine content as a function of holding time. As shown in Fig. 6, the dechlorination rate remains approximately 99% at different holding times. The dechlorination rate reached the maximum value of 99.28% at a holding time of 60 min. However, the chlorine content in the calcination products first decreases from 30 min to 60 min, and then increases with prolonged holding time from 60 min to 150 min. The chlorine content reached the minimum value of 0.13% at a holding time of 60 min. The morphological changes of the calcination products obtained at different holding times were given in Fig. 7. It can be clearly seen from Fig. 7 that with the increase of holding time, the calcined product exhibits significant sintering, along with the occurrence of densification and the formation of large agglomerates. So this phenomenon is attributed to sintering induced by in the raw materials under 900°C and excessively long holding time, which hindered chloride volatilization and was consistent with experimental observations. Considering both production efficiency and the chlorine content requirements for ceramic glaze-grade zinc oxide, the optimal holding time was determined to be 60 min.

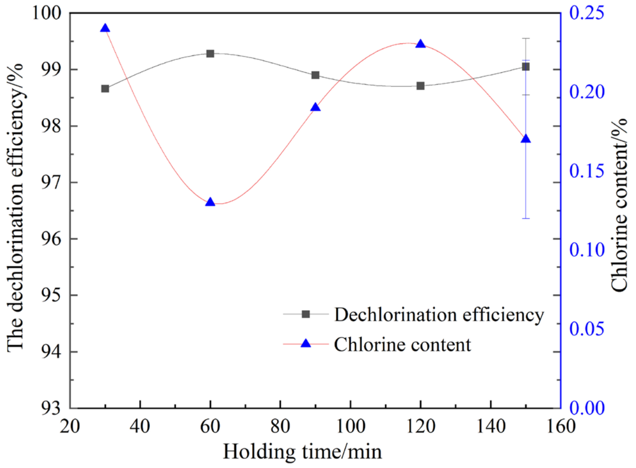

Fig. 6. The dechlorination rates and chlorine content in the calcined products as a function of holding time

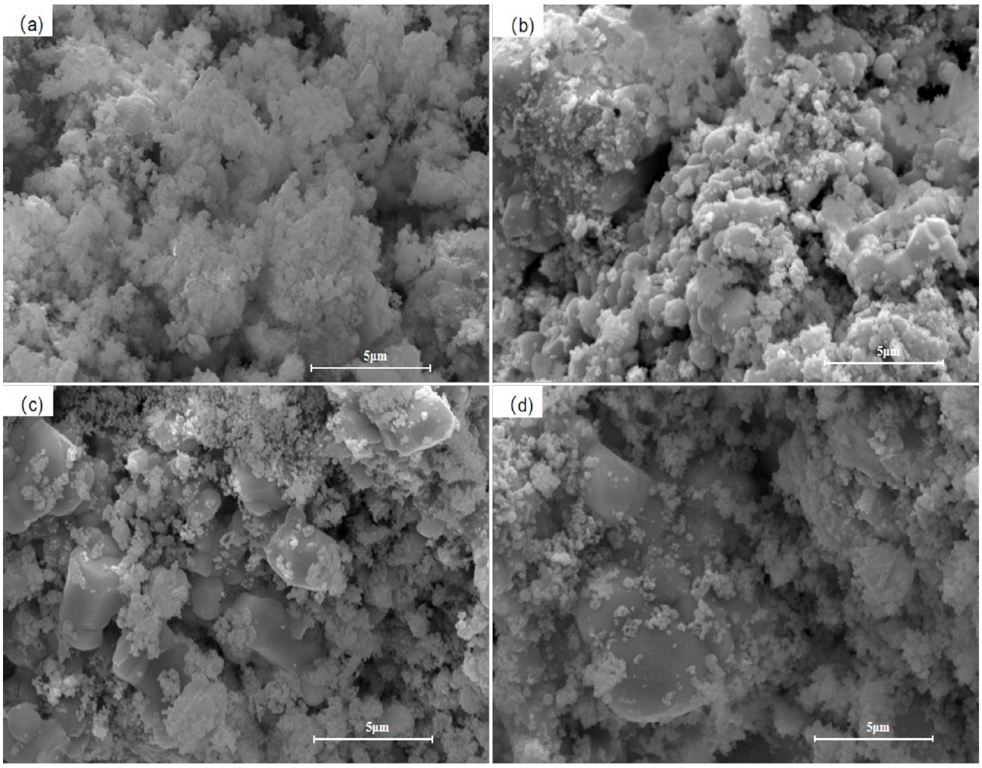

Fig. 7. SEM micrographs of calcined product with different holding time: (a) 60 min, (b) 90 min, (c) 120 min and (d) 150 min

### 3.6. Effect of microwave heating power on chlorine removal

The content of chlorine in calcination products and dechlorination rate were investigated microwave heating power over a range of 70-95%. Experimental conditions were shown as follows: the experimental raw material mass was 200 g, the calcination temperature was 900°C and the holding time was 60 min. Fig. 8 shows the dechlorination rate as a function of heating power. A maximum dechlorination rate of 99.28% was achieved at the minimum heating power of 70%. Increasing the heating power conversely resulted in lower dechlorination rates (<99%) . Meanwhile, the calcined product reached the minimum chlorine content of 0.13% at 70% heating power. The chlorine content in calcination products increased to varying degrees with higher heating power. This phenomenon attributed to the unique characteristics of microwave heating. Unlike conventional methods, microwaves generate rapid and uniform volumetric heating. Since heating power dictates the temperature ramp rate, higher heating power shortens the duration required to reach target temperatures, consequently reducing the hot-dip galvanizing ash's residence time in the microwave field. The heating time as a function of heating power is shown in Fig. 9. Fig. 9 shows that the heating time increases from 54 min to 120 min as the heating power decreasing from 95% to 70%. As shown in Fig. 9, the cumulative thermal effect during the heating stage has a significant impact on dechlorination. The insufficient cumulative residence time of the raw material in the microwave field can result in incomplete chlorine volatilization. Therefore, considering both product quality and energy consumption, the optimum heating power is determined to be 70%.

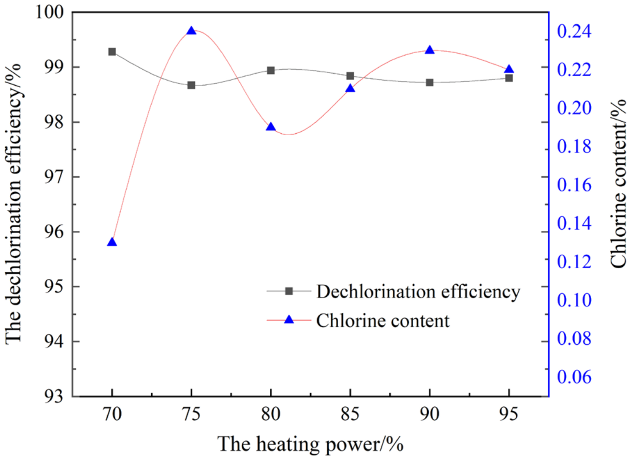

Fig. 8. The dechlorination rates and chlorine content in the calcined products as a function of heating power

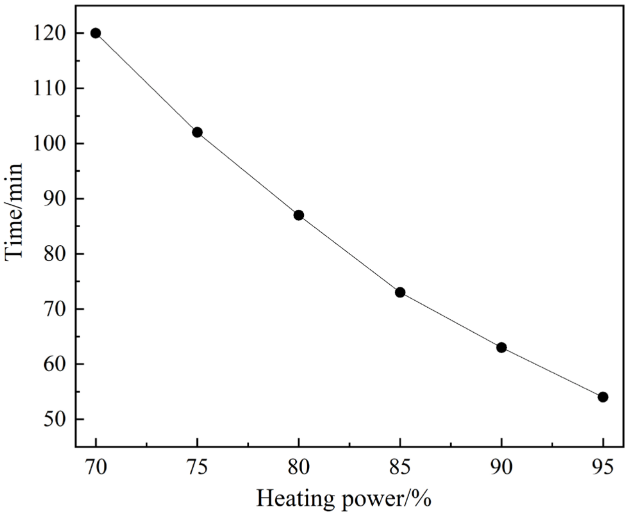

Fig. 9. The heating time as a function of heating power

### 3.7. Characterization of calcined products prepared at the optimum condition

Fig. 10 shows the SEM image of the product obtained at the optimum parameters with the calcination temperature of 900°C, the holding time of 60 min and the microwave heating power of 70%. It can be seen that the sample has a uniform porous microstructure with obvious void formations, primarily caused by the volatilization of $ZnCl_2$ and other volatile species. XRD patterns of the product is shown in Fig. 11. As shown in Fig. 11, the calcined product is mainly composed of ZnO, along with a small amount of $Al_2O_3$ and PbO.

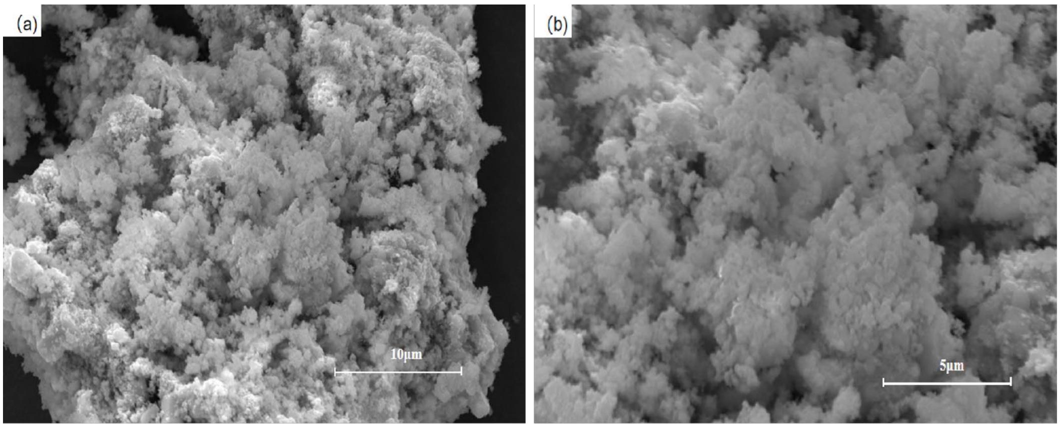

Fig. 10. SEM images of the calcined product at the optimum condition (the calcination temperature of 900℃, the holding time of 60 min and the microwave heating power of 70%)

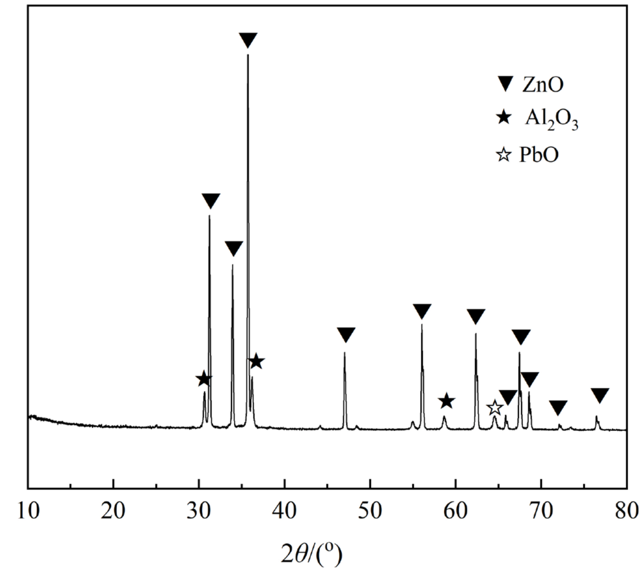

Fig. 11. The XRD pattern of calcined product under optimal process conditions

### 3.8. The energy consumption and economic evaluation

The rotary kiln is commonly employed for dichlorination from the hot-dip galvanizing ash in enterprises, which requires the combustion of a significant amount of natural gas within the kiln. The required volume of natural gas for this process varies significantly depending on the chlorine content of the zinc ash. Based on the industrial operational data of a calcined zinc oxide factory in Yunnan province for ceramic glaze preparation, the natural gas consumption is 700 m$^3$ to process 1 ton hot-dip galvanizing ash with 15% chlorine content. Calculated at a natural gas price of 3.50 CNY per cubic meter, The energy consumption and economic evaluation comparison between rotary kiln industrial production and microwave muffle furnace laboratory experiment processing 1t hot-dip galvanizing ash are also shown in TABLE 3.

TABLE 3

The energy consumption and economic evaluation comparison between rotary kiln industrial production and microwave muffle furnace laboratory experiment processing 1t hot-dip galvanizing ash

| Furnace type | Chlorine content/% | Energy consumption and economic evaluation/CNY | kJ/kgCl |
|---|---|---|---|
| rotary kiln | ~15 | ~2,450 | 181,675 |
| microwave muffle furnace | 11.59 | 343 | 21,298 |

In experiments, the heating current is approximately 5A, while the holding current is about 1A. So the energy consumption and economic evaluation for microwave muffle furnace treatment of 1t hot-dip galvanizing ash with 11.59% chlorine content are as follows:

$$Q_{heating} = \\ = 2350.86\ \text{J/(kg}\cdot\text{°C)} \times 1000\,\text{kg} \times (900\text{°C} - 25\text{°C}) = \\ = 2{,}057{,}002{,}500\,\text{J} \tag{1}$$

$$Q_{holding} \approx 0.2 \times Q_{heating} = 411{,}400{,}500\,\text{J} \tag{2}$$

$$Q_{sum} = Q_{heating} + Q_{holding} = \\ = 2{,}057{,}002{,}500\,\text{J} + 411{,}400{,}500\,\text{J} = \\ = 2{,}468{,}403{,}000\,\text{J} = 685.67\,\text{kW}\cdot\text{h} \tag{3}$$

Therefore, the electricity cost required to process 1 ton of hot-dip galvanizing ash with microwave muffle furnace is about 343 CNY, calculated at an electricity price of 0.50 CNY/kW·h.

In summary, according to the data in TABLE 3, using microwave calcination to process 1t of high-chlorine hot-dip galvanizing ash saves at least 2,107 CNY compared to the traditional rotary kiln method.

## 4. Conclusions

(1) The high chlorine hot-dip galvanizing ash can be heated rapidly under microwave irradiation. Microwave energy can selectively heat chloride compounds with strong microwave-absorption properties, thereby enhancing their volatilization and separation. A 200 g sample reaches 900°C in approximately 47 min at 0.8 kW microwave power, demonstrating the low energy consumption of microwave calcination for hot-dip galvanizing ash treatment.

(2) The optimized parameters were obtained as follows: heating temperature of 900°C, holding time of 60 min and heating power of 70%. At the optimum conditions, the chlorine with high content of 11.59% was efficiently removed to 0.13%, which exceeding the quality requirements for ceramic glaze-grade zinc oxide (<0.3%) and the dechlorination rate reached 99.28%. While in the industrial rotary kiln processing of hot-dip galvanizing ash with 15% chlorine content to produce ceramic glaze-grade zinc oxide, the roasting temperature is generally maintained between 1200-1300°C, and the dechlorinated product contains less than 0.5% chlorine.

(3) Microwave calcination of hot-dip galvanizing ash offers significant energy and cost savings while effective avoidance of $CO_2$ emissions. Compared to traditional rotary kiln processing, this method reduces costs by 2,107 CNY processing per ton hot-dip galvanizing ash.

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## REFERENCES

[1] P. Mass, P. Peissker,Handbook of Hot-Dip Galvanization. Weinheim,Wiley (2011).

[2] X.H.Yuan, M.Y. He, S.M. Wang, X. Zhao, X.J. Zhao, Formation Cause and Rrecovering Technology of Hot Ggalvanizing Dross. Yunnan Metallurgy **36** (1), 32-36 (2007) (in Chinese).

[3] D.W. Shao, Z.R. He, Y.H. Zhang, Y. He, Research Progress of Hot-dip Galvanizing Technology. Hot Work Technol. **41**, 100-103 (2012). DOI: http://doi:10.1007/s11783-011-0280-z

[4] E. Rudnik, Hydrometallurgical Recovery of Zinc from Industrial Hot Dipping Top Ash. T. Nonferr. Metal. Soc. **30** (8), 2239-2255 (2020). DOI: http://doi:10.1016/S1003-6326(20)65375-4

[5] C.S. Uppalwar, A.N. Thakur, J.G. Gujar, S.S. Sonawane, Chapter Sixteen-Recovery of Zinc from A Variety of Industrial Waste. In: Metal Value Recovery from Industrial Waste Using Advanced Physicochemical Treatment Technologies, India, 335-363 (2025).

[6] P. Dvoák, J. Jandová, Hydrometallurgy Recovery of Zinc from Hot Dip Galvanizing Ash. Hydrometallurgy **7** (1), 29-33 (2005). DOI: http://doi:10.1016/j.hydromet.2004.10.007

[7] M.K. Jha, V. Kumar, R.J. Singh, Review of hydrometallurgical recovery of zinc from industrial wastes. Resour. Conserv. Recy. **33** (1), 1-22(2001).
DOI: http://doi:10.1016/S0921-3449(00)00095-1

[8] K. Blasková, J. Trpevská, J. Piroková, M. Laubertová, Zinc Waste Treatment Originated during Hot-Dip Galvanizing. World Metall-Erzmetall **70** (4), 223-226 (2017).

[9] M. Barakat, Pyrometallurgical Processing of Zinc Ash and Flue Dust. Acta Metall. Slovaca **9** (4), 259-269 (2003).

[10] A.B. Shi, Technology Research on Preparation of Nanometer ZnO by Hot Galvanizing Dross. Zhenjiang: Jiangsu University of Science and Technology, (2011) (in Chinese).

[11] M.Y. Huang, Z.G. Deng, X.B. Li, C. Wei, New Technologies and Research Progress on Zinc Recovery from HDG Residue. Mining & Metallurgy **28** (4), 70-74 (2019) (in Chinese).
DOI: http://doi:10.3969/j.issn.1005-7854.2019.04.012

[12] L. Han, B. Yang, B.Z. Yang, Y.N. Dai, D.C. Liu, B.Q. Xu, Zinc Recovering from Hot Galvanized Scraps by Vacuum Distillation. Chinese Journal of Vacuum Science and Technology **29**, 101-104 (2009) (in Chinese).

[13] Jarmila Trpevská, Blanka Hokovetá, Jaroslav Brianin, Katarina Jana Piroková, The Pyrometallurgical Recovery of Zinc from the Coarse-Grained Fraction of Zinc Ash by Centrifugal Force. Int. J. Miner. Process **143**, 25-33 (2015).
DOI: http://doi:10.1016/j.minpro.2015.08.006

[14] M.H. Habibie, F.S.H. Krismastuti, F.F.V. Septama, Novel Synthesis of ZnO Nanostructure from Galvanization Waste for Antibacterial Application. Mater. Lett. **356**, 135603-135606 (2024).
DOI: http://doi:10.1016/j.matlet.2023.135603

[15] E. Rudnik, Recovery of Zinc from Zinc Ash by Leaching in Sulphuric Acid and Electrowinning. Hydrometallurgy **188**, 256-263 (2019). DOI: http://doi:10.1016/j.hydromet.2019.07.006

[16] B.S. Chahar, V. Singh, M.K. Bhadu, S. Hadas, A. N. Bhagat, K. Mondal, Recovery and Utilization of Zinc Dross for Sacrificial Anode Cathodic Protection of Steel Structures. Sustain. Mater. and Techno. **41**, e01046 (2024).
DOI: https://doi.org/10.1016/j.susmat.2024.e01046

[17] F.W. Li, A Method for Producing Zinc Oxide for Ceramic Glazes Using Hot-Dip Galvanizing Ash. CN202110032833.6, 2025-07-08 (2025) (in Chinese).

[18] F.Ç. Şahin, B. Derin, O. Yücel, Chloride Removal from Zinc Ash. Scand. J. Metall. **29**, 224-230 (2000).
DOI: https://doi.org/10.1034/j.1600-0692.2000.d01-26.x

[19] N. Güresin, Y.A. Topkaya, Dechlorination of A Zinc Dross. Hydrometallury **49**, 179-187 (1998).
DOI: https://doi.org/10.1016/s0304-386x(98)00012-7

[20] Y. Mi, Volatility Kinln Processing Zinc Casting Dross Dechlorinate Practice. Sichuan Nonferrous Metals **3**, 29-30 (2007) (in Chinese).
DOI: https://doi.org/10.3969/j.issn.1006-4079.2007.03.006

[21] Q. Zheng, L.B. Zhang, J.H. Peng, S.H. Ju, Study on Dechlorination of Zinc Dross by Microwave Roasting. Mining and Metallurgy **22**, 67-71 (2013) (in Chinese).
DOI: https://doi.org/10.3969/j.issn.1005-7854.2013.04.015

[22] Z.Y. Guo, C.Y. Huang, W.P. Feng, et al., The New Technique Advance of Removing Chlorine and Fluorine of Intermediate Material from Lead and Zinc Metallurgy by Microwave Roasting. Vacuum Electronics **5**, 115-121 (2013) (in Chinese).
DOI: http://doi:10.16540/j.cnki.cn11-2485/tn.2013.05.002

[23] A.Y. Ma, X.M. Zheng, C.Y. Sun, Y.G. Luo, S. Li, Microwave Dielectric Droperties and Temperature Increasing Characteristics on Zinc Oxide Dust with High Content of Cl. Journal of Central South University (Science and Technology) **46**, 410-415 (2015) (in Chinese).
DOI: http://doi:10.11817/j.issn.1672-7207.2015.02.005

[24] M.A. Harahsheha, S. Kingma, L.A. Makhadmah, I.E. Hamilton, Microwave Treatment of Electric Arc Fdust with PVC: Dielectric Characterization and Pyrolysis-Leaching. J. Hazard Mater. **274**, 87-97 (2014). DOI: http://doi:10.1016/j.jhazmat.2014.03.019

[25] C.H. Liu, New Process Research on Microwave Heating Applications Based on Dielectric Properties of Metallurgical Materials. Kunming: Kunming University of Science and Technology. (2014) (in Chinese).

[26] Y.F. Niu, Y.C. Yang, T. Le, S.B. Fang, S.Y. Gong, S.H. Tian, S.H. Ju, L. Xu, Enhancing the Dechlorination of CuCl Residue Using a Microwave Sulfation-Rroasting Method: Process Optimization and Mechanism Investigation. J. Environ. Chem. Eng. **11** (2), 109362 (2023).
DOI: https://doi.org/10.1016/j.jece.2023.109362