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Research on Formulation Optimization of Submerged Arc Welding Flux Prepared from Steel Slag

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Abstract

Steel slag is used to develop high-value submerged arc welding flux, achieving high-value conversion of industrial solid waste and easing environmental pressure, but the current research lacks systematic multi-component formula optimization and fails to build accurate quantitative correlation between flux minerals components and weld metal elements. In this study, the extreme vertex design method was used to optimize the formulation of steel slag-based flux, and 25 SJ501 steel slag-based submerged arc fluxes were prepared accordingly. The selected flux formulation's welds were characterized through weld visual inspection, ultrasonic testing, metallographic analysis and microhardness testing, and the results showed that these properties were

comparable to commercial flux SJ501. Based on the test results of 25 formulas for weld elements, a mathematical regression model was established to predict and analyze the content of each element in the weld. Analysis of variance (ANOVA) of the regression models showed that all seven established models for the weld elements were statistically significant and can effectively explain the variation in each elemental content of the weld. Among these models, those for Al, Mn, and Ni exhibited superior performance, with R^2 values of 0.780, 0.704 and 0.720 and p-values of 0.009, 0.020 and 0.006, respectively, indicating that these three models have higher accuracy and reliability in prediction. This study provided a key technical support for the scientific research and development of steel slag-based submerged arc welding fluxes.

Keywords: Steel slag; SJ501 flux; mathematical model; ANOVA

1.Introduction

According to the World Steel Association's *World Steel Statistics 2024*, the global annual crude steel output exceeded 1.888 billion tons^[1]. Steel slags are by-products in the steelmaking process, accounting for 15%-20% of crude steel production. They are rich in components such as SiO_2 and Al_2O_3 and exhibits excellent melting characteristics and fluxing properties^[2-5].

The submerged arc welding flux, as a critical auxiliary material in the welding process, significantly affects the microstructure, mechanical properties, and welding process stability of the weld metal^[6,7]. With the rapid development of the steel industry and the growing demand for high-quality welded joints, the development of high-performance and eco-friendly fluxes has attracted extensive research attention. Traditional fluxes are usually composed of various minerals, and their proportions have a significant influence on the properties of the weld^[8,9].

To systematically investigate the relationship between multicomponent flux formulations and the resulting welds, the extreme vertex design method is adopted in this study. This method is based on the design principle of multicomponent systems, in

which component constraints are defined and experimental designs are carried out at the extreme vertices within the formulation design space. This method has been successfully applied to the formulation optimization of composite materials^[10-12]. In this experiment, the steel slag content was fixed at 40%, and four components, including titanium dioxide, fused magnesia, bauxite, and fluorite (i.e., TiO_2 , MgO , Al_2O_3 and CaF_2 , were added. Then, 25 types of fluxes were designed using the extreme vertex design method. This method efficiently screened out the optimal addition ratios of the four components and thus significantly reduced the number of required experiments^[13,14].

This study aimed to design steel slag-based flux formulations via the extreme vertex design method, establish regression models between flux composition and weld metal element content, and analyze the internal morphology and microstructure of the welds. The significance and predictive ability of the regression models were verified via analysis of variance (ANOVA), and the effects of different components on key weld elements including Al, Mn and Ni were clarified.

2.Experimentation

2.1 Experimental materials

Q235 steel plates (300 mm × 200 mm × 10 mm) were used as the base material, and H08MnA welding wire was employed. The chemical compositions of Q235 steel plates and H08MnA welding wires were listed in Table 1, and both were supplied by a company based in Taiyuan. The commercial sintered flux employed in this experiment was SJ501, which was purchased from a company in Zhengzhou. This study used electric furnace slag as raw material to prepare SJ501 submerged arc flux, and the solid waste of electric furnace slag was supplied by a casting enterprise in Shanxi Province. The mineral powder used in the experiment was purchased from Lingshou County Shuolong Mineral Products Processing Factory, with a particle size of 100-200 mesh and a purity of 97%-99%. Sodium silicate (water glass) was used as the binder, which was obtained from Guangzhou Suixin Chemical Co., Ltd. with a modulus of 3.1,

and accounted for 20% of the total mass of the flux raw materials.

The SJ501 flux was an Al-Ti type acidic sintered welding flux, with a typical particle size of 10-60 mesh and an alkalinity of approximately 0.7. Its main components were listed in Table 2. This flux was widely used for the welding of low-carbon steel and low-alloy structural steel.

Table 1 Chemical composition of base metal and welding wire elements.

material/(content%)	C	Si	Mn	Cr	Ni	Cu	S	P
Q235	0.152	0.233	0.570	0.001	0.001	0.030	0.014	0.0119
H08MnA	0.072	0.043	0.920	0.021	0.010	0.150	0.011	0.014

Table 2 The composition ranges of electric furnace slag used in the experiment and commercial flux SJ 501

material/(content%)	SiO ₂ +TiO ₂	Al ₂ O ₃ +MnO ₂	CaO+MgO	CaF ₂
electric furnace slag	28.67	66.57	1.10	0.00
SJ 501 flux	25-35	50-60	5-10	5-10

2.2 Experimental process

Steel slags and mineral raw materials were crushed to a particle size of ≤ 1 mm using a jaw crusher, followed by sieving with 100-mesh and 150-mesh vibrating sieves to ensure uniform particle sizes^[15]. The steel slags were further ground and sieved through a 100-mesh sieve. According to the 25 flux formulations, each raw material was accurately weighed. The ingredients were thoroughly mixed in a mixer for 10 min to achieve homogeneous mixing. The mixture was fed into a granulator, and an appropriate amount of water glass solution was sprayed to form particles with a diameter of 2-3 mm. The granules were successively sieved through 20-mesh and 50-mesh sieves to obtain uniformly graded 20-50 mesh steel slag submerged arc welding flux. The uniformly formed pellets were dried in an oven at 220 °C for 40 minutes, followed by calcination in a muffle furnace at 800 °C for 1.5 hours to prepare the

required steel slag flux. The prepared flux was sealed in moisture-proof bags^[16].

Before welding, the flux was dried in an oven at 180 °C for 2 h to prevent moisture from interfering with the welding process^[17]. The welding parameters were set as follows: welding current of 320 A, welding speed of 25 cm·min⁻¹, welding voltage of 30 V, and a 5 mm distance between the welding gun and the base metal. The submerged arc welding machine employed was model MZ-ZK-630.

2.3 Experimental formula design method

First, the contents of various components in the steel slag were determined by XRF spectrometry.

$$z = \max \{x_i\}, \quad i=1,2,3\dots \quad (1)$$

In detail, determine the target flux based on the z-value and establish c_i in Formula (2). Within the upper and lower limits of the mass fraction of each component in the target flux, the maximum addition amount of steel slag was a. Then, the b_i value was determined by the difference compensation method^[18].

The experimental approach for the formulation employed the difference compensation method, specifically as follows:

$$a \begin{pmatrix} x_1 \\ \vdots \\ x_i \end{pmatrix} + \begin{pmatrix} b_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & b_i \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_i \end{pmatrix} = \begin{pmatrix} c_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & c_i \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_i \end{pmatrix} \quad (2)$$

$$0 \leq b_i \leq 1; \quad 0 \leq c_i \leq 1, i=1,2,3\dots n \quad (3)$$

z

– The main component with the highest proportion in the composition of steel slags

a — Steel slag addition amount;

b_i — Component compensation amount;

c_i — Required component quantities for target flux;

x_i — Substances required for submerged arc welding flux.

According to the XRF analysis results in Table 3, the primary constituents of steel slag are SiO₂, Al₂O₃ and MnO₂. As shown in Table 2, the SJ501 flux formulation requires substantial amounts of Al₂O₃ and MnO₂. Therefore, to enhance the utilization

rate of steel slag, the SJ501 flux was selected as the target flux.

Table 3 XRF test results of electric furnace slag

material/(content%)	CaO	SiO ₂	Fe ₂ O ₃	MgO	Al ₂ O ₃	TiO ₂	MnO ₂
electric furnace slag	1.07	26.57	4.52	0.03	20.63	2.10	42.94

The extreme vertex design method was adopted in this study for flux formulation design. As an experimental design technique, the extreme vertex method was particularly suitable for multi-component formulation design^[19]. First, the influencing factors and their corresponding levels were determined. Based on the flux composition and welding quality requirements, the key factors affecting flux performance, such as SiO₂, CaF₂ and Al₂O₃, as well as their variation ranges, were identified^[20,21].

Based on the raw material requirements of SJ501 flux listed in Table 2 and the composition of electric furnace steel slag presented in Table 3, the blending ratio of electric furnace steel slag was controlled at 40% in the experiment. Since the steel slag lacked the required TiO₂, MgO, CaF₂ and part of Al₂O₃, calculations using the differential compensation method formula indicated that additional additives were needed, namely: titanium dioxide (13.53%-23.53%), fused magnesia (4.56%-9.56%), bauxite (24.57%-34.57%), and fluorite (5%-10%). Subsequently, the formulation design was performed using Minitab software. To facilitate formulation design and subsequent mathematical modeling, the required addition ranges of these minerals were adjusted to: titanium dioxide: 15%-25%; fused magnesia: 5%-10%; bauxite: 25%-35%; fluorite: 5%-10%. Notably, the total mass fraction of these four mineral additives had to collectively reach 60%.

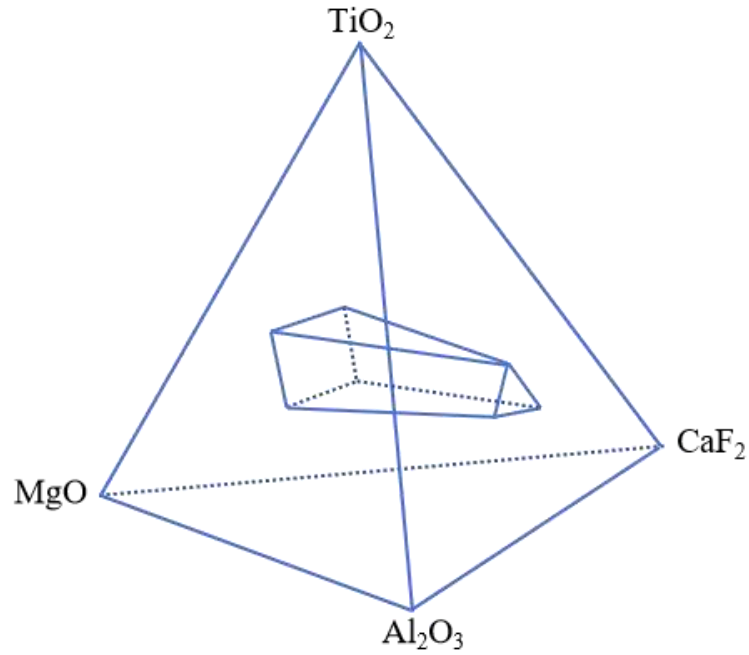


Fig. 1 Extreme vertex design concept diagram

As shown in Fig 1, after adjusting the proportion of four minerals added, the formulation distribution was confined within the depicted prism. The special points were in one-to-one correspondence with the serial numbers in Table 4. The central point (point type 0) corresponded to Formulation No. 17; the pyramid vertices (point type 1) included Formulations No. 1, 9, 13, 15, 19, 20 and 24; the midpoints of each pyramid edge (point type 2) included Formulations No. 2, 3, 4, 6, 7, 8, 11, 16, 21, 22 and 25; and the midpoints of each pyramid face (point type 3) included Formulations No. 5, 10, 12, 14, 18 and 23.

After determining the appropriate range of mineral content, the extreme vertex design method in Minitab software was used to generate the components of 25 steel slag based flux formulations (see Table 4).

Table 4 Formula for steel slag flux

Serial Number	Point Type	TiO ₂	MgO	Al ₂ O ₃	CaF ₂
1	1	20.0	5.0	25.0	10.0
2	2	15.0	7.5	27.5	10.0
3	2	15.0	10.0	27.5	7.5
4	2	17.5	7.5	25.0	10.0
5	3	16.7	6.7	26.7	10.0
6	2	15.0	7.5	32.5	5.0
7	2	20.0	5.0	30.0	5.0
8	2	17.5	10.0	27.5	5.0
9	1	20.0	10.0	25.0	5.0
10	3	20.0	7.5	25.0	7.5
11	2	17.5	10.0	25.0	7.5
12	3	15.0	7.5	30.0	7.5
13	1	15.0	5.0	30.0	10.0
14	3	18.8	5.0	28.8	7.5
15	1	25.0	5.0	25.0	5.0
16	2	15.0	5.0	32.5	7.5
17	0	17.9	7.1	27.9	7.1
18	3	18.8	7.5	28.8	5.0
19	1	15.0	5.0	35.0	5.0
20	1	15.0	10.0	25.0	10.0
21	2	22.5	7.5	25.0	5.0
22	2	17.5	5.0	27.5	10.0
23	3	16.7	10.0	26.7	6.7
24	1	15.0	10.0	30.0	5.0
25	2	22.5	5.0	25.0	7.5

Point Type:1 (Vertex) ;2 (Mid point of the line) ;3 (Mid point of the surface) ;0
(Center point)



Fig.2 25 sets of electric furnace slag flux formula samples

Fig.2 showed the final prepared flux samples prepared using electric furnace steel slag (No. 1-25). The mass of each sample was 400-500 g, with a uniform particle size distribution within the range of 20-50 mesh. Calcination was carried out at 800 °C for 1.5 h.

2.4 Characterization methods

By comparing the flux formulations at each vertex in the experimental design table with those of the commercial flux, further characterizations were conducted on the welds prepared with the electric furnace steel slag fluxes at seven specific vertex positions (No. 1, 9, 13, 15, 19, 20 and 24) and the commercial flux. The welds were conducted to ultrasonic flaw detection, microstructural analysis, and microhardness testing.

Visual Inspection: Visible defects on the weld surface can be directly identified through visual inspection. Based on surface abnormalities, preliminary inferences about potential internal defects can be made, and key aspects of visual inspection included the weld profile, surface defects, and the transition between the weld and the base metal.

Ultrasonic Testing (UT): This technique enables the rapid, non-destructive, and accurate detection, localization, evaluation, and diagnosis of various internal defects (e.g., cracks, inclusions, and gas pores) in workpieces ^[22]. In this study, a Leeb522 ultrasonic flaw detector manufactured by a company in Jinan was used.

Microhardness Testing: Microhardness is a type of indentation hardness representing a comparative hardness test used to reflect the resistance of materials to penetration by other hard objects ^[23]. In this study, a Time5330 microhardness tester produced by a company in Jinan was employed for microhardness testing.

Metallurgical Microscope: This instrument is used to observe the microstructure of materials, such as grains, inclusions, and dislocations, in order to evaluate material properties. In this study, a CSW-5E200M metallurgical microscope manufactured by a company in Shenzhen was employed for microstructure observation.

X-ray Fluorescence Spectrometry (XRF): This method is used to determine the type and concentration of trace elements in materials. In this study, an Epsilon 1 energy-dispersive XRF spectrometer manufactured by a Dutch company was employed for elemental analysis, where the tested elements range from sodium (Na) to americium (Am), with concentrations spanning from parts per million (ppm) to 100%.

3.Results and Discussion

3.1 Visual Inspection of Weld Appearance



Fig. 3 25 sets of formulas corresponding to the appearance of weld seams

Fig.3 showed the appearance of welds prepared with electric furnace steel slag-based flux formulations No.1-25. During welding, the arc exhibited excellent stability and the flux demonstrated excellent slag detachability, with no slag adhesion observed on the weld surface. The weld surface was free of defects such as pitting, porosity, inclusions, and undercut. The weld beads were straight and free from distortion. The weld surface exhibited a uniform color, with no signs of oxidation or discoloration.

Vertices represented extreme combinations constrained by boundary conditions, which covered the entire mixing ratio space with the minimum number of experimental points, captured performance extremes and maximum variation effects, and ensured that all formula points satisfied the constraint conditions. Seven vertex formulas of electric furnace steel slag flux (Formula No. 1, 9, 13, 15, 19, 20 and 24) were selected from the formulation table and compared with a commercial flux. The corresponding welds fabricated by these seven vertex-position fluxes and the commercial flux were

subsequently characterized and analyzed in depth, and the characterization items involved ultrasonic flaw detection, microstructural morphology observation and microhardness testing.

3.2 Ultrasonic testing

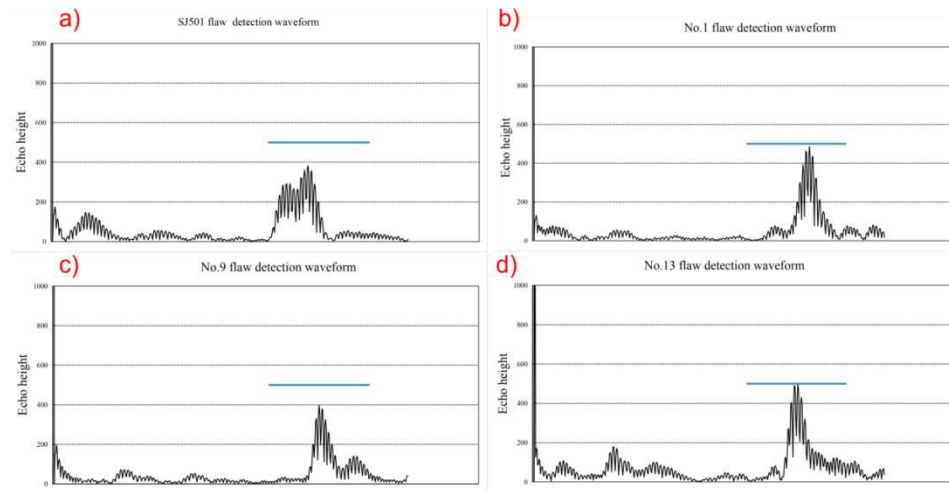


Fig. 4 (a,b,c,d)Ultrasonic testing images of welds corresponding to SJ501, No.1, No.9 and No.13

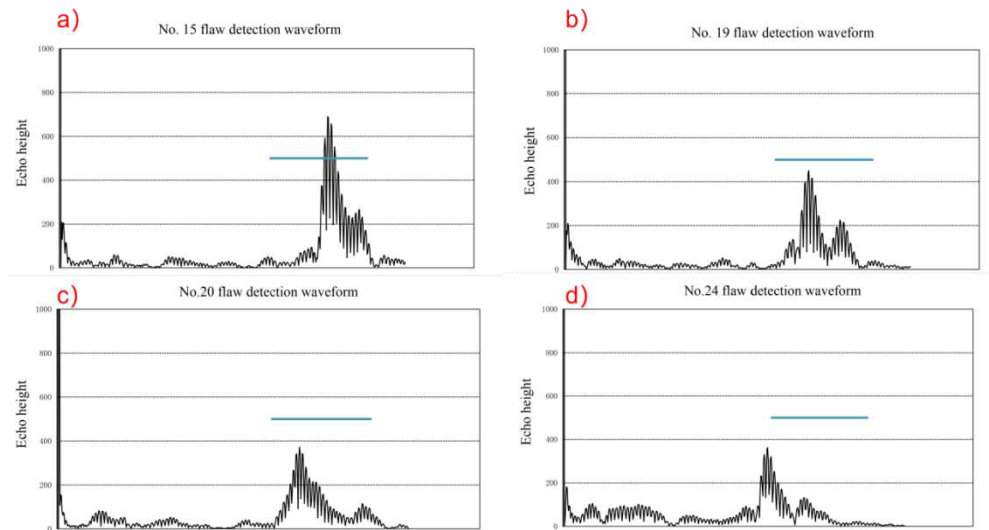


Fig. 5 (a,b,c,d)Ultrasonic testing images of welds corresponding to No.15, No.19, No.20 and No.24

A single-element angle probe was employed for ultrasonic flaw detection, and the

workpiece thickness was 10 mm. The detection procedure involved directing the angle probe toward the weld seam and moving it smoothly along the weld edge from one side to the other. The A-scan signals were observed, and the waveforms at positions with higher or wider peaks were recorded. As shown in Figs.4 and 5, ultrasonic inspection images of the corresponding welds were presented for flux formulations No. 1, 9, 13, 15, 19, 20 and 24, as well as the commercial SJ 501 flux. The peaks in the ultrasonic flaw detection signals suggested that the ultrasonic waves had encountered an interface or defect within the weld metal. The peak height was related to the reflection intensity of the ultrasonic waves. The higher the peak, the larger the reflective interface associated with the defect. The peak width reflected the defect size, a wider peak corresponded to a larger defect or a wider defect surface. Flat regions indicated that ultrasonic waves had propagated through a uniform material without encountering significant interfaces or defects. From the peak heights and widths in the ultrasonic signals, it could be seen that the welds corresponding to fluxes No. 1, 9, 13, 19, 20 and 24 exhibited similar peak characteristics to those of the weld produced with the commercial SJ 501 flux, indicating similar internal structures. In addition, the ultrasonic images for fluxes No. 1, 9 and 19 showed large flat regions, demonstrating that the welds prepared using the electric furnace slag-based flux were free of obvious internal defects.

3.3 Characterization of microstructure

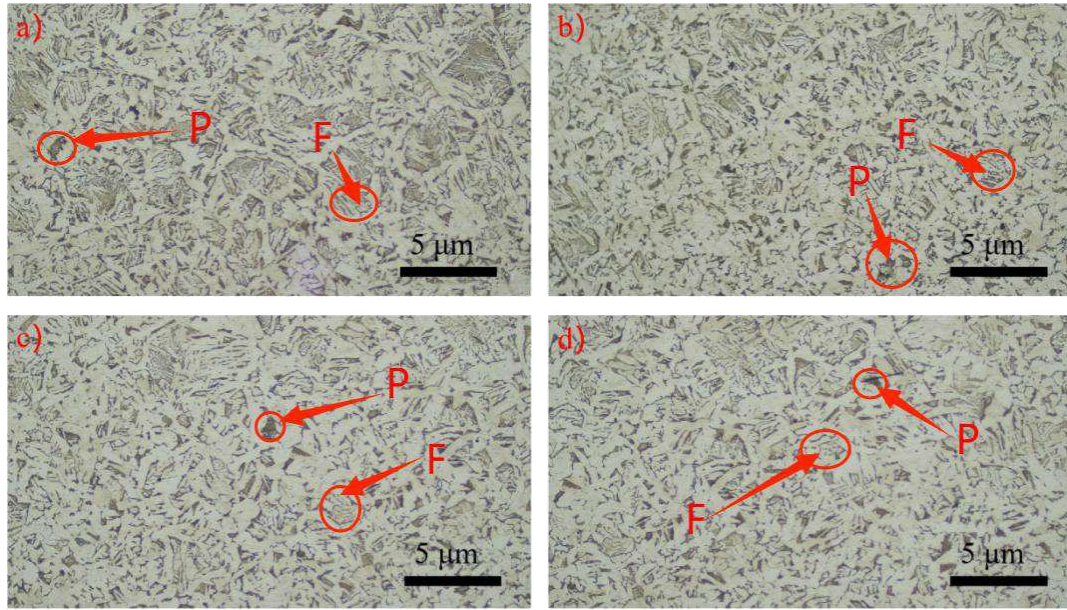


Fig. 6 (a, b, c, d) The corresponding weld micrographs of SJ 501 and formula No.1, No.9 and No.13 fluxes in sequence

Figs.6 and 7 showed the metallographic micrographs of the weld cross-sections. Before metallographic observation, the weld sections were pretreated. First, the sections were polished smoothly with sandpaper, progressing from coarse to fine grit, and polishing was maintained in the same direction until the surfaces were sufficiently smooth. After polishing, the weld regions were etched with a 4% nitric acid-alcohol solution for approximately 10 seconds, followed by thorough rinsing with running water^[24]. Subsequently, the surfaces were dried with a hair dryer and observed under a metallographic microscope. As shown in Fig 6, the metallographic micrographs corresponded to the weld zones prepared with the commercial flux SJ 501 and the self-designed fluxes No. 1, 9 and 13. No obvious porosity or inclusion defects were observed in the weld cross-sections, indicating that the internal microstructures of the welds were good.

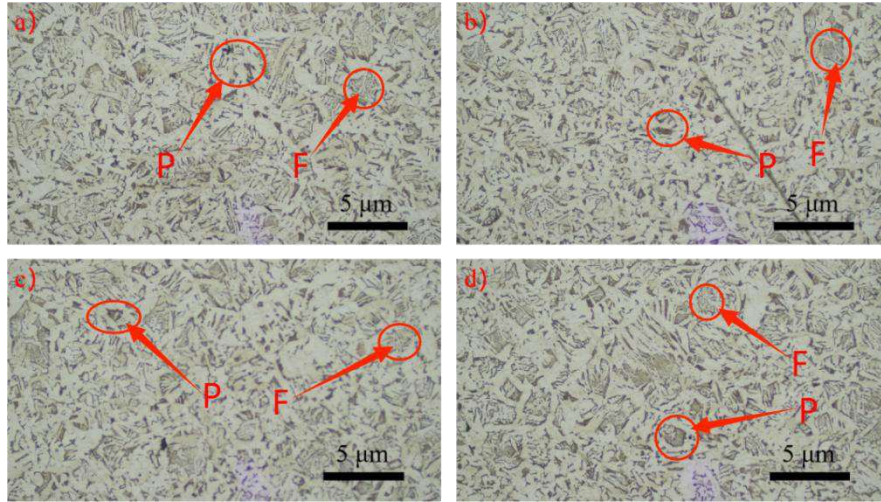


Fig. 7 (a, b, c, d) are the corresponding weld micrographs of formula No.15, No.19, No.20 and No.24 fluxes in sequence

As shown in Fig.7, the metallographic micrographs of the weld zones corresponding to fluxes No. 15, 19, 20 and 24 were presented. Similarly, no obvious porosity or inclusion defects were observed in the four weld cross-sections. The weld microstructures formed by the eight fluxes were also similar, mainly consisting of pearlite(P) and ferrite(F)^[25], which indicated that they could provide favorable strength and toughness for the weld metal^[26]. This verified that the electric furnace slag-based flux could satisfy the welding requirements.

3.4 Microhardness testing

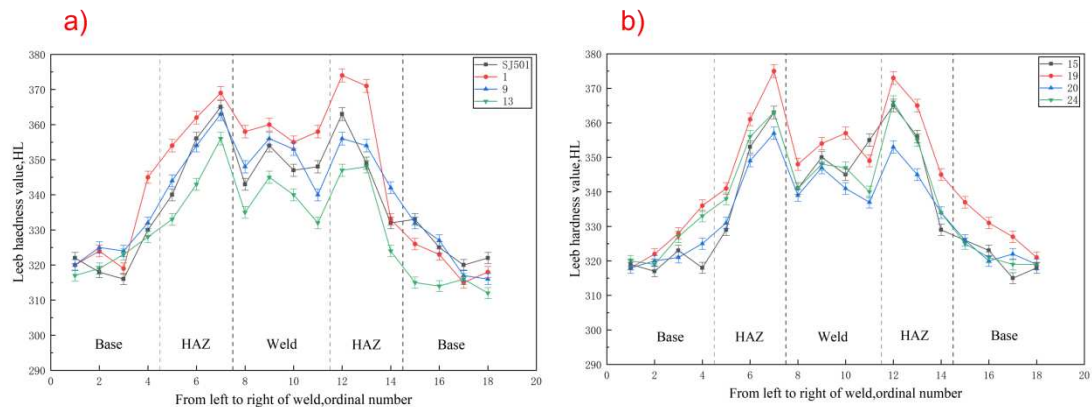


Fig. 8 (a) Microhardness distribution of welds SJ501, No.1, No.9 and No.13
; (b) Microhardness distribution of welds No.15, No.19, No.20 and No.24.

Before testing the microhardness of the weld profile, the weld was first cut, and the weld profile was polished to a smooth finish prior. The weld profile was stably fixed on the stage, starting from the base metal, passing through the heat affected zone (HAZ), welding zone, and then back to the HAZ and base metal for measurement. The test data were plotted into a line graph to observe the hardness distribution trend.

As shown in Fig.8(a), the microhardness distributions of welds prepared with the commercial SJ 501 flux and formula fluxes No. 1, 9 and 13 were presented. Fig.8(b) displayed the microhardness distributions of welds prepared with formula fluxes No. 15, 19, 20 and 24. It could be observed that the microhardness values of the weld profile exhibited a trend of increasing first and then decreasing from the base metal to the HAZ and subsequently to the weld zone. The microhardness of the HAZ was relatively high because it was adjacent to both the weld and the base metal, and thus experienced faster heating and higher cooling rates than the weld zone during the welding process. Consequently, the hard and brittle phases such as martensite tended to form in the HAZ, resulting in higher hardness. In contrast, the weld zone had a relatively large volume with slow heat dissipation and a low cooling rate, leading to a coarse microstructure and low hardness. The base metal was the least affected, showing the lowest and most stable hardness values^[27]. The maximum hardness appeared in the HAZ near the fusion line, indicating that phase transformation or microstructural changes had occurred in this region. From the figures, the overall microhardness of welds No. 1 and No. 19 was relatively high, with maximum values of 174 HV and 175 HV, respectively, while that of weld No. 13 was relatively low, with a minimum value of 112 HV. Generally, a higher hardness value corresponded to better wear resistance but relatively lower toughness. The microhardness values of the other five welds were relatively close. Therefore, welds produced with the seven vertex-position formula fluxes showed the same microhardness evolution trend as those welded with the commercial SJ 501 flux. The overall microhardness of No. 1 and 19 was higher, indicating favorable wear resistance.

3.5 Composition analysis of welds formed by 25 steel slag-based fluxes



Fig. 9 Processing sample diagram for testing the composition content of weld seam components

Fig.9 showed the processed specimens used for the analysis of weld element content. Prior to testing with an XRF spectrometer, the weld specimens required pretreatment. The surface of submerged arc welds might contain oxide layers, flux residues, or other contaminants, which could affect the measurement results of elements. Therefore, the weld samples were cleaned and polished to expose a flat, smooth internal weld surface for testing.

Table 5 presented the test results of welds corresponding to the 25 flux formulations, obtained via XRF spectrometry. The analysis primarily focused on the contents of carbon (C), silicon (Si), manganese (Mn), chromium (Cr), copper (Cu), aluminum (Al), and nickel (Ni) in the welds.

Table 5 Results of elemental content measured for 25 sets of steel slag-based welds seam

Serial Number	C/%	Si/%	Mn/%	Cr/%	Cu/%	Al/%	Ni/%
1	0.069	0.236	0.274	0.062	0.028	0.004	0.015
2	0.071	0.235	0.290	0.063	0.034	0.006	0.017
3	0.074	0.282	0.319	0.063	0.033	0.004	0.015
4	0.075	0.225	0.320	0.059	0.035	0.005	0.016
5	0.073	0.258	0.315	0.063	0.034	0.005	0.015
6	0.074	0.315	0.313	0.062	0.034	0.004	0.014
7	0.072	0.297	0.293	0.059	0.029	0.004	0.014
8	0.077	0.212	0.344	0.062	0.034	0.003	0.013
9	0.073	0.288	0.316	0.063	0.035	0.004	0.014
10	0.072	0.212	0.291	0.058	0.029	0.003	0.013
11	0.070	0.280	0.318	0.060	0.034	0.003	0.013
12	0.078	0.256	0.341	0.065	0.035	0.004	0.015
13	0.071	0.272	0.296	0.061	0.029	0.005	0.016
14	0.069	0.289	0.287	0.058	0.028	0.004	0.014
15	0.069	0.256	0.250	0.055	0.024	0.003	0.013
16	0.070	0.299	0.295	0.058	0.035	0.004	0.014
17	0.067	0.324	0.258	0.052	0.025	0.003	0.012
18	0.071	0.341	0.306	0.065	0.034	0.004	0.015
19	0.069	0.386	0.292	0.064	0.033	0.005	0.016
20	0.067	0.260	0.258	0.055	0.026	0.003	0.013
21	0.070	0.291	0.284	0.059	0.035	0.003	0.014
22	0.069	0.248	0.277	0.058	0.027	0.004	0.015
23	0.077	0.271	0.316	0.060	0.035	0.003	0.012
24	0.077	0.303	0.325	0.060	0.034	0.004	0.014
25	0.069	0.255	0.269	0.057	0.027	0.003	0.012

3.6 Establishment, ANOVA Analysis and Verification of Mathematical Model for Steel Slag-based Flux Formulaton

TiO₂, MgO, CaF₂ and Al₂O₃ were used as the four mineral variables (independent variables) selected from the 25 formulations, and the elemental contents in the welds were taken as the dependent variables. A quaternary regression model was established using SPSS software. After optimization and adjustment, the mathematical model equations for the weld elements C, Si, Mn, Cr, Cu, Al and Ni were presented as follows.

$$\begin{aligned} \text{Al} = & 0.025 - 0.164 * \text{TiO}_2 + 0.646 * \text{MgO} + 1.083 * \text{CaF}_2 + 0.583 * \text{TiO}_2 * \text{Al}_2\text{O}_3 \\ & - 2.061 * \text{MgO} * \text{Al}_2\text{O}_3 - 13.856 * \text{MgO} * \text{CaF}_2 - 2.462 * \text{Al}_2\text{O}_3 * \text{CaF}_2 \\ & - 4.333 * \text{TiO}_2 * \text{MgO} * \text{Al}_2\text{O}_3 - 10.714 * \text{TiO}_2 * \text{Al}_2\text{O}_3 * \text{CaF}_2 + 34.127 * \text{MgO} * \text{Al}_2\text{O}_3 * \text{CaF}_2 \\ & + 81.597 \text{TiO}_2 * \text{MgO} * \text{Al}_2\text{O}_3 * \text{CaF}_2 \end{aligned}$$

$$\begin{aligned} \text{Mn} = & -2.886 + 17.363 * \text{MgO} + 2.570 * \text{Al}_2\text{O}_3 + 18.478 * \text{CaF}_2 + 33.840 * \text{TiO}_2 * \text{Al}_2\text{O}_3 \\ & + 7.148 * \text{TiO}_2 * \text{CaF}_2 - 378.209 * \text{MgO} * \text{CaF}_2 - 232.369 * \text{TiO}_2 * \text{MgO} * \text{Al}_2\text{O}_3 \\ & + 1099.189 * \text{TiO}_2 * \text{MgO} * \text{CaF}_2 - 297.890 + 667.202 * \text{TiO}_2 * \text{Al}_2\text{O}_3 * \text{CaF}_2 \end{aligned}$$

$$\begin{aligned} \text{Si} = & 0.556 - 8.943 * \text{TiO}_2 * \text{MgO} - 12.874 * \text{TiO}_2 * \text{CaF}_2 + 46.506 * \text{MgO} * \text{CaF}_2 \\ & - 172.344 * \text{MgO} * \text{Al}_2\text{O}_3 * \text{CaF}_2 \end{aligned}$$

$$\begin{aligned} \text{C} = & -0.114 + 1.913 * \text{MgO} + 2.271 * \text{CaF}_2 + 3.226 * \text{TiO}_2 * \text{Al}_2\text{O}_3 + 1.223 * \text{MgO} * \text{Al}_2\text{O}_3 \\ & - 31.362 * \text{MgO} * \text{CaF}_2 - 41.225 * \text{TiO}_2 * \text{MgO} * \text{Al}_2\text{O}_3 - 43.735 * \text{TiO}_2 * \text{Al}_2\text{O}_3 * \text{CaF}_2 \\ & + 649.661 \text{TiO}_2 * \text{MgO} * \text{Al}_2\text{O}_3 * \text{CaF}_2 \end{aligned}$$

$$\begin{aligned} \text{Cr} = & -1.220 + 5.826 * \text{MgO} + 1.725 * \text{Al}_2\text{O}_3 + 9.373 * \text{TiO}_2 * \text{Al}_2\text{O}_3 + 41.201 * \text{TiO}_2 * \text{CaF}_2 \\ & - 12.132 * \text{MgO} * \text{Al}_2\text{O}_3 - 56.972 * \text{MgO} * \text{CaF}_2 + 12.240 * \text{Al}_2\text{O}_3 * \text{CaF}_2 \\ & - 170.377 * \text{TiO}_2 * \text{Al}_2\text{O}_3 * \text{CaF}_2 + 199.303 * \text{MgO} * \text{Al}_2\text{O}_3 * \text{CaF}_2 \end{aligned}$$

$$\text{Ni} = 0.098 - 0.236 * \text{TiO}_2 + 0.565 * \text{MgO} + 1.361 * \text{CaF}_2 - 3.547 * \text{MgO} * \text{Al}_2\text{O}_3$$

$$-17.608 * \text{MgO} * \text{CaF}_2 - 4.216 * \text{Al}_2\text{O}_3 * \text{CaF}_2 + 2.998 * \text{TiO}_2 * \text{MgO} * \text{Al}_2\text{O}_3 \\ - 9.120 * \text{TiO}_2 * \text{Al}_2\text{O}_3 * \text{CaF}_2 + 60.636 * \text{MgO} * \text{Al}_2\text{O}_3 * \text{CaF}_2$$

$$\text{Cu} = -0.181 + 0.461 * \text{Al}_2\text{O}_3 + 1.663 * \text{CaF}_2 + 4.757 * \text{TiO}_2 * \text{MgO} - 1.620 * \text{MgO} * \text{Al}_2\text{O}_3 \\ - 21.179 * \text{MgO} * \text{CaF}_2 + 64.945 * \text{MgO} * \text{Al}_2\text{O}_3 * \text{CaF}_2$$

The ANOVA results of the model were presented in Table 6. A combined analysis was performed based on the regression equations and ANOVA results [28-30]. The results showed that all seven models were statistically significant and could effectively explain the variations in elemental contents in the welds. The regression models for Al, Mn and Ni exhibited better performance, with corresponding coefficients of determination R^2 of 0.780, 0.704 and 0.720, respectively. These values indicated that the models could explain 78.0% of the variation in Al content, 70.4% of the variation in Mn content, and 72.0% of the variation in Ni content in the welds, which represented relatively high explanatory power. The corresponding p-values were 0.009, 0.020 and 0.006, respectively, all of which were less than 0.05, thus suggesting that the models were globally significant. This implied that at least one independent variable had a significant effect on the contents of Al, Mn and Ni in the welds. In summary, the models showed satisfactory goodness of fit, along with favorable explanatory and predictive capabilities.

Table 6 Model overview and ANOVA analysis

element	name	coefficient	R ²	mean square	F	P	significance
Al	model		0.780	< 0.0001	4.163	0.009	significant
	constant	0.025				0.367	insignificant
	TiO ₂	-0.164				0.026	significant
	MgO	0.646				0.046	significant
	CaF ₂	1.083				0.003	significant
	TiO ₂ *Al ₂ O ₃	0.583				0.126	insignificant
	MgO*Al ₂ O ₃	-2.061				0.056	insignificant
	MgO*CaF ₂	-13.856				0.010	significant
	Al ₂ O ₃ *CaF ₂	-2.462				0.026	significant
	TiO ₂ *MgO*Al ₂ O ₃	-4.333				0.354	insignificant
	TiO ₂ *Al ₂ O ₃ *CaF ₂	-10.714				0.033	significant
	MgO*Al ₂ O ₃ *CaF ₂	34.127				0.051	insignificant
	TiO ₂ *MgO*Al ₂ O ₃ *CaF ₂	81.597				0.225	insignificant
Mn	model		0.704	0.001	3.337	0.020	significant
	constant	-2.886				0.064	insignificant
	MgO	17.363				0.054	insignificant
	Al ₂ O ₃	2.570				0.059	insignificant
	CaF ₂	18.478				0.043	significant
	TiO ₂ *Al ₂ O ₃	33.840				0.058	insignificant
	TiO ₂ *CaF ₂	7.148				0.693	insignificant
	MgO*CaF ₂	-378.209				0.029	significant
	TiO ₂ *MgO*Al ₂ O ₃	-232.369				0.108	insignificant
	TiO ₂ *MgO*CaF ₂	1099.189				0.038	significant
	TiO ₂ *Al ₂ O ₃ *CaF ₂	-297.890				0.069	insignificant
	MgO*Al ₂ O ₃ *CaF ₂	667.202				0.035	significant
Si	model		0.561	0.005	6.390	0.002	significant

	constant	0.556			0.000	significant
	TiO ₂ *MgO	-8.943			0.046	significant
	TiO ₂ *CaF ₂	-12.874			0.006	significant
	MgO*CaF ₂	46.506			0.214	insignificant
	MgO*Al ₂ O ₃ *CaF ₂	-172.344			0.200	insignificant
C	model	0.641	< 0.0001	3.467	0.015	significant
	constant	-0.114			0.414	insignificant
	MgO	1.913			0.067	insignificant
	CaF ₂	2.271			0.023	significant
	TiO ₂ *Al ₂ O ₃	3.226			0.028	significant
	MgO*Al ₂ O ₃	1.223			0.188	insignificant
	MgO*CaF ₂	-31.362			0.022	significant
	TiO ₂ *MgO*Al ₂ O ₃	-41.225			0.046	insignificant
	TiO ₂ *Al ₂ O ₃ *CaF ₂	-43.735			0.033	significant
	TiO ₂ *MgO*Al ₂ O ₃ *CaF ₂	649.661			0.026	significant
Cr	model	0.653	< 0.0001	3.141	0.024	significant
	constant	-1.220			0.003	significant
	MgO	5.826			0.001	significant
	Al ₂ O ₃	1.725			0.002	significant
	TiO ₂ *Al ₂ O ₃	9.373			0.003	significant
	TiO ₂ *CaF ₂	41.201			0.001	significant
	MgO*Al ₂ O ₃	-12.132			0.004	significant
	MgO*CaF ₂	-56.972			0.002	significant
	Al ₂ O ₃ *CaF ₂	12.24			0.003	significant
	TiO ₂ *Al ₂ O ₃ *CaF ₂	-170.377			0.001	significant
	MgO*Al ₂ O ₃ *CaF ₂	199.303			0.003	significant

Ni	model		0.720	< 0.0001	4.288	0.006	significant
	constant	0.098				0.010	significant
	TiO ₂	-0.236				0.031	significant
	MgO	0.565				0.156	insignificant
	CaF ₂	1.361				0.003	significant
	MgO*Al ₂ O ₃	-3.547				0.043	significant
	MgO*CaF ₂	-17.608				0.023	significant
	Al ₂ O ₃ *CaF ₂	-4.216				0.019	significant
	TiO ₂ *MgO*Al ₂ O ₃	2.998				0.225	insignificant
	TiO ₂ *Al ₂ O ₃ *CaF ₂	-9.120				0.002	significant
	MgO*Al ₂ O ₃ *CaF ₂	60.636				0.031	significant
Cu	model		0.600	< 0.0001	3.624	0.014	significant
	constant	-0.181				0.027	significant
	Al ₂ O ₃	0.461				0.021	significant
	CaF ₂	1.663				0.081	insignificant
	TiO ₂ *MgO	4.757				0.012	significant
	MgO*Al ₂ O ₃	-1.620				0.096	insignificant
	MgO*CaF ₂	-21.179				0.084	insignificant
	MgO*Al ₂ O ₃ *CaF ₂	64.945				0.101	insignificant

In Fig 10, (a), (b), (c) and (d) showed the normal probability plots corresponding to the multivariate linear regression models for the weld elements Al, Mn, Si and C based on the 25 sets of formulated fluxes, respectively. These plots were used to verify the normality of the standardized residuals in the regression models. The points in the figures represented the cumulative probabilities of the standardized residuals, and the diagonal lines represented the theoretical normal distribution.

It could be seen from the figures that most points in the residual plots for the four

elements (Al, Mn, Si and C) were distributed along the diagonal lines, indicating that the residuals approximately followed a normal distribution. Although slight deviations existed at both ends of the plots-possibly caused by tail deviations in the data, the overall residual distribution supported the application of the multivariate linear model for analysis, confirming that the normality assumption of the model residuals was valid. In addition, several points in the lower-left corner of the residual plots for Mn and C exhibited minor deviations.

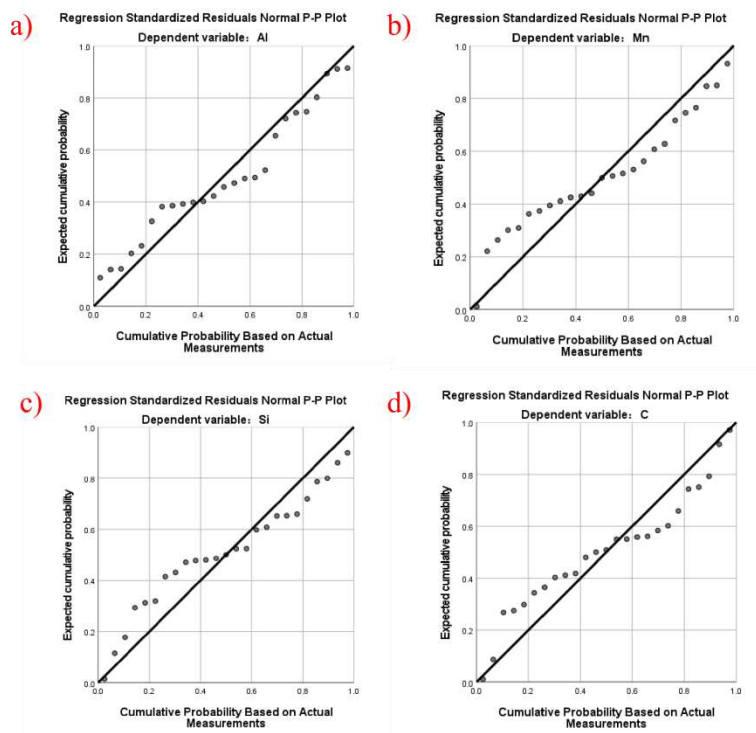


Fig.10 Residual plots of Al, Mn, Si, and C element models

Fig.11(a), (b) and (c) presented the normal probability plots of the residuals for the multivariate linear models predicting the Cr, Ni and Cu contents in the weld seam based on the 25 groups of formulated fluxes. Most data points in the plots were close to the straight lines, with only a few points deviating slightly, indicating that the residuals generally followed a normal distribution. This confirmed that the normality assumption of the model residuals was satisfied, although the distribution was not perfectly normal. Minor deviations could be observed in the lower-left and upper-right regions of the residual plot for Cr, as well as in the lower-left region of the residual plot for Cu.

It could be seen from the figures that most points in the residual plots for the three elements (Cr, Ni and Cu) were distributed along the diagonal lines, indicating that the residuals approximately followed a normal distribution. Although slight deviations existed at both ends of the plots-possibly caused by tail deviations in the data, the overall residual distribution supported the application of the multivariate linear model for analysis, confirming that the normality assumption of the model residuals was valid.

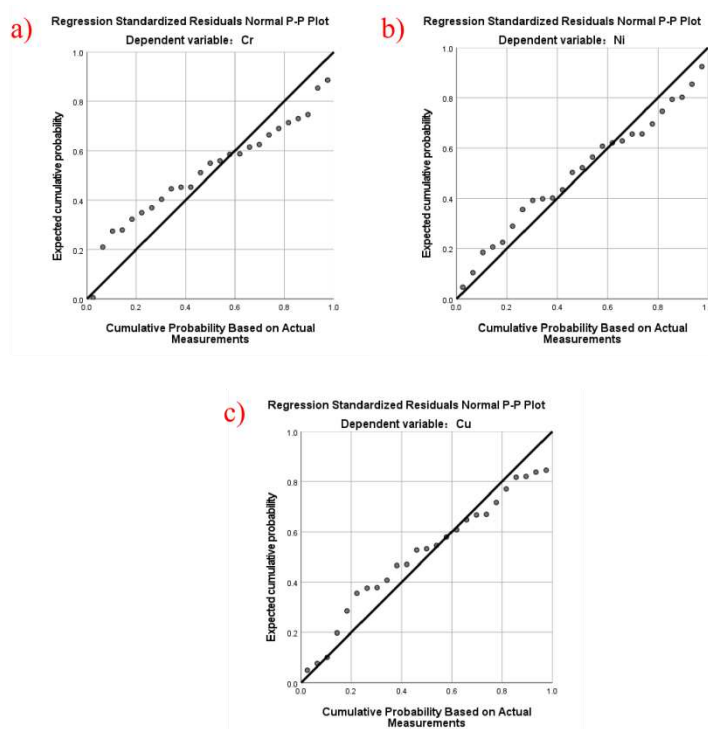


Fig. 11 Residual plots of Cr, Ni, and Cu element models

Conclusion

The results show that the welds formed by 25 SJ501 steel slag-based submerged arc fluxes had no obvious defects and the weld beads were smooth and uniform. No significant differences were observed between the welds produced by the seven vertex formulations (Formula No. 1, 9, 13, 15, 19, 20 and 24) and those produced by the commercial flux SJ 501. The welds made with the formulated fluxes exhibited a dense internal structure, without internal defects such as pores and inclusions, and possessed

a favorable ferrite-pearlite microstructure. ANOVA of the regression models for the seven weld elements showed that all seven models were significant and can effectively explain the variations in the elemental contents of the welds. Among these models, those for Al, Mn, and Ni demonstrated superior performance, with coefficients of determination (R^2) of 0.780, 0.704 and 0.720, and p-values of 0.009, 0.020 and 0.006, respectively. In conclusion, the SJ 501 flux prepared using electric furnace steel slag met the application requirements in terms of weld appearance and microstructure. In addition, the established regression models between the formulated flux compositions and the weld elemental contents provided a reliable basis for the interpretation and prediction of weld chemistry.

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