

Complex Deoxidation Characteristics Analysis of Acid-family welding Electrode

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ABSTRACT

This study investigates the complex deoxidation characteristics of acid-family welding electrodes, focusing on the combined use of ferromanganese and ferrosilicon as deoxidizers. The research addresses the critical issue of oxygen content in deposited metal, which adversely affects weld quality. Traditional approaches using individual deoxidizers have shown limited effectiveness in acid systems. This study employs a thermodynamic analysis to explore the synergistic effects of combining deoxidizers, aiming to enhance deoxidation efficiency and improve mechanical properties. The methodology involves both theoretical calculations and experimental validation. Thermodynamic modeling was used to predict the formation of complex deoxidation products, such as $MnO \cdot SiO_2$, and their stability at various temperatures. Experimental trials were conducted using nine different compositions of welding electrodes, with varying percentages of ferromanganese (10-14%) and ferrosilicon (4-8%). The oxygen content in the weld pool was measured using a gas analyzer after welding under controlled conditions. The findings reveal that the complex deoxidation approach significantly reduces oxygen levels in the weld pool compared to using ferromanganese alone. Specifically, the optimal combination of 12% ferromanganese and 4% ferrosilicon achieved the lowest oxygen content, enhancing the weld's mechanical properties. This study provides a scientific basis for optimizing deoxidation processes in acid-family welding electrodes, offering a potential breakthrough in welding metallurgy. The results suggest that the influence of ferrosilicon is more pronounced than that of ferromanganese, with most silicon participating in deoxidation while some manganese remains in the deposited metal. These insights could lead to improved welding techniques and material performance in industrial applications.

Keywords: complex deoxidation, acid-family welding electrode

1 Introduction

Oxygen in deposited metal is a detrimental element that significantly reduces the impact value of weld joints. Consequently, deoxidation is a crucial step in the welding process. Typically, acid welding electrodes incorporate materials that form basic oxides, such as ferromanganese (20%), to facilitate deoxidation. In contrast, basic welding electrodes utilize materials that form acid oxides, including ferrosilicon, ferrotitanium, and aluminum, for the same purpose [1] [2] [3]. The presence of acid oxides in the welding slag of acid electrodes complicates the transition rate of manganese, resulting in suboptimal mechanical properties due to high oxygen content in the deposited metal [4] [5]. Recent studies have challenged the effectiveness of using individual deoxidizers in acid systems, advocating for the use of multiple deoxidizers in basic systems. It has been observed that the simultaneous use of silicon and manganese as deoxidizers significantly reduces the oxygen content in the weld pool compared to using silicon alone [6]. This enhanced deoxidation capability is

attributed to the lower concentration of deoxidation products formed during complex deoxidation. While the effects of complex deoxidation in basic welding electrodes are documented, there is a lack of research on its impact when enhancing basicity in acid-family welding electrodes [7] [8] [9]. This study aims to fill this gap by analyzing the complex deoxidation characteristics of acid-family welding electrodes, focusing on the synergistic use of ferromanganese and ferrosilicon to improve deoxidation efficiency and mechanical properties. This revised introduction provides a clear context for the research, highlighting the problem, existing solutions, and the study's focus.

2 Method

The methodology of this study combines theoretical and experimental approaches to analyze the deoxidation characteristics of acid-family welding electrodes. The research focuses on the synergistic effects of using ferromanganese and ferrosilicon as deoxidizers. Thermodynamic modeling was employed to predict the formation and stability of complex deoxidation products, such as $\text{MnO}\cdot\text{SiO}_2$, under various conditions. Nine different electrode compositions were prepared, varying the ferromanganese content from 10% to 14% and the ferrosilicon content from 4% to 8%. The welding experiments were conducted under controlled conditions with an AC current of 250 A, an arc voltage of 28 V, and a weld rate of 10 m/h. Following welding, the oxygen content in the deposited metal was measured using a gas analyzer, with samples taken from the weld pool and subjected to vacuum melting. The experimental results were compared with theoretical predictions to validate the effectiveness of the complex deoxidation approach, aiming to optimize the deoxidizer composition for improved weld quality and mechanical properties.

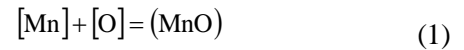
3 Result and Discussion

The study on the thermodynamics complex deoxidation

Complex deoxidation theory

In welding metallurgy, deoxidation is a critical process to reduce the oxygen content in deposited metal, thereby improving the mechanical properties of the weld. The complex deoxidation theory explores the simultaneous use of multiple deoxidizers to enhance deoxidation efficiency beyond what is achievable with individual elements [10]. In this study, the focus is on the combined use of ferromanganese and ferrosilicon as deoxidizers in acid-family welding electrodes. When deoxidation is performed using only ferromanganese, the reaction can be represented as $[\text{Mn}]+[\text{O}]=(\text{MnO})$, with the equilibrium constant $K(\text{MnO})$ defined by the activity of MnO in the slag. The oxygen content $[\%O]$ in the deposited metal is inversely related to the activity of MnO, which is influenced by the equilibrium constant and the manganese content $[\%Mn]$ [11]. To lower the oxygen content, it is essential to decrease the activity of MnO in the slag. The introduction of ferrosilicon alongside ferromanganese leads to additional reactions: $[\text{Si}]+2[\text{O}]=(\text{SiO}_2)$ and the formation of a complex product $(\text{MnO}\cdot\text{SiO}_2)$. This complex deoxidation product reduces the activity of MnO, thereby enhancing the deoxidation effect. The formation of $(\text{MnO}\cdot\text{SiO}_2)$ lowers the concentration of deoxidation products in the slag, improving the overall deoxidation efficiency. The thermodynamic stability of these reactions is crucial. The equilibrium constant K and free energy changes ΔG are calculated to determine the conditions under which these reactions are most favorable. The study finds that complex deoxidation significantly reduces the oxygen content in the weld pool compared to using ferromanganese alone, with the optimal combination being 12% ferromanganese and 4% ferrosilicon [12]. This approach not only improves the deoxidation efficiency but also enhances the mechanical properties of the weld, offering a promising advancement in welding technology. This explanation provides a clear and detailed understanding of the complex deoxidation theory, highlighting the theoretical basis and practical implications of the study.

Deoxidation reaction is as follows when deoxidation performs with only ferromanganese.



Where equilibrium constant is as follows

$$K_{(\text{MnO})} = \frac{a_{(\text{MnO})}}{a_{[\text{Mn}]} \cdot a_{[\text{O}]}} \quad (2)$$

Hence

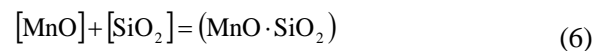
$$[\% \text{O}] = \frac{a_{(\text{MnO})}}{K_{\text{MnO}} \cdot [\% \text{Mn}]} \quad (3)$$

Where $K_{(\text{MnO})} = \exp\left(-\frac{G_{\text{MnO}}}{RT}\right)$ is equilibrium constant for reaction, $a_{(\text{MnO})}$ is activity of MnO in slag, $[\% \text{Mn}]$ is content of Mn in deposited metal.

Since $K(\text{MnO})$ is constant under the determined temperature, activity $a_{(\text{MnO})}$ of MnO in slag should be decreased to lower the amount of oxygen in deposited metal.

When being deoxidation with a variety of deoxidizer at the same time, activity in deoxidation product is lowered and the effect in deoxidation is improved. [1,3,4]

When using ferromanganese and ferrosilicon as deoxidizer, the reaction formulas are as follows.

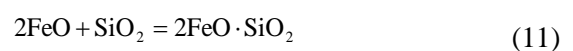
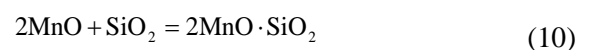
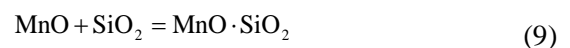
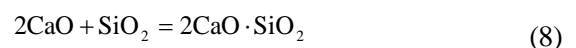
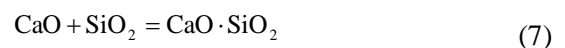


Join deoxidation product ($\text{MnO} \cdot \text{SiO}_2$) is produced through the above reaction process.

Making $\text{MnO} \cdot \text{SiO}_2$ by the combination of MnO and SiO, activity of MnO in slag is lowered.

Free energy formable for products of complex deoxidtion formable in acid welding electrode

The formation of complex deoxidation products in acid welding electrodes involves a series of thermodynamically driven reactions. These reactions are crucial for reducing the oxygen content in the weld pool and enhancing the mechanical properties of the weld. The key reactions for the formation of complex deoxidation products include [13] [14] :



The free energy change ($\Delta G_{\circ T}$) for these reactions is a critical parameter that determines the feasibility and extent of the reactions at given temperatures. The free energy is calculated using the equation:

$$\Delta G_T^\circ = \Delta H_{298}^\circ - \Delta S_{298}^\circ \times T - (\Delta C_0 M_0 + \Delta C_1 M_1 + \Delta C_2 M_2 + \Delta C_{-2} M_{-2}) \quad (12)$$

where $\Delta H_{\circ 298}$ is the enthalpy change, $\Delta S_{\circ 298}$ is the entropy change, and ΔC_i and M_i are heat capacity coefficients and temperature function values, respectively.

The study calculates the free energy and equilibrium constant values for these reactions at various temperatures, revealing that the stability of the compounds varies with temperature. For instance, $\text{CaO}\cdot\text{SiO}_2$ becomes less stable at higher temperatures, while $\text{MnO}\cdot\text{SiO}_2$ and $\text{FeO}\cdot\text{SiO}_2$ become more stable as the temperature decreases [15]. This thermodynamic behavior influences the effectiveness of deoxidation and the quality of the weld. The results indicate that $\text{MnO}\cdot\text{SiO}_2$ is particularly effective as a deoxidation product due to its favorable thermodynamic properties, making it a suitable choice for improving weld quality in acid-family electrodes [16]. This explanation provides a detailed and scientifically rigorous discussion of the thermodynamics involved in complex deoxidation, suitable for an international journal.

The results which calculated the free energy value and equilibrium constant value to the temperature for products of complex deoxidation are shown in Table-1.

Table 1. The free energy value and equilibrium constant value to the temperature for products of complex deoxidation.

Temperature (K)	$\text{CaO}\cdot\text{SiO}_2$		$2\text{CaO}\cdot\text{SiO}_2$		$\text{MnO}\cdot\text{SiO}_2$		$2\text{MnO}\cdot\text{SiO}_2$		$2\text{FeO}\cdot\text{SiO}_2$	
	ΔGT	Kp	ΔGT	Kp	ΔGT	Kp	ΔGT	Kp	ΔGT	Kp
1800	$-2.8\cdot 10^5$	$1.50\cdot 10^8$	$-1.35\cdot 10^5$	8281	$-2.59\cdot 10^4$	5.64	$-1.44\cdot 10^4$	2.60	$3.33\cdot 10^4$	0.107
1900	$-3.0\cdot 10^5$	$1.98\cdot 10^8$	$-1.35\cdot 10^5$	5073	$-2.58\cdot 10^4$	5.13	$-1.23\cdot 10^4$	2.18	$3.59\cdot 10^4$	0.103
2000	$-3.2\cdot 10^5$	$3.05\cdot 10^8$	$-1.35\cdot 10^5$	3264	$-2.57\cdot 10^4$	4.70	$-1.02\cdot 10^4$	1.86	$3.85\cdot 10^4$	0.098
2100	$-3.4\cdot 10^5$	$3.05\cdot 10^8$	$-1.34\cdot 10^5$	2190	$-2.56\cdot 10^4$	4.35	$-0.80\cdot 10^4$	1.60	$4.12\cdot 10^4$	0.094
2200	$-3.6\cdot 10^5$	$3.68\cdot 10^8$	$-1.34\cdot 10^5$	1523	$-2.56\cdot 10^4$	4.06	$-0.60\cdot 10^4$	1.40	$4.38\cdot 10^4$	0.091
2300	$-3.8\cdot 10^5$	$4.37\cdot 10^8$	$-1.34\cdot 10^5$	1094	$-2.55\cdot 10^4$	3.80	$-0.40\cdot 10^4$	1.24	$4.64\cdot 10^4$	0.088
2400	$-4.0\cdot 10^5$	$5.11\cdot 10^8$	$-1.33\cdot 10^5$	807	$-2.54\cdot 10^4$	3.58	$-0.19\cdot 10^4$	1.10	$4.90\cdot 10^4$	0.085
2500	$-4.2\cdot 10^5$	$5.91\cdot 10^8$	$-1.33\cdot 10^5$	610	$-2.54\cdot 10^4$	3.39	$-0.11\cdot 10^4$	0.99	$5.17\cdot 10^4$	0.083

From table-1, we have found that free energy for $\text{CaO}\cdot\text{SiO}$ is lowered when the temperature is raised. This compounds are unstable when the temperature is lowered. Free energy for $2\text{CaO}\cdot\text{SiO}_2$, $\text{MnO}\cdot\text{SiO}_2$, $2\text{MnO}\cdot\text{SiO}_2$, $2\text{FeO}\cdot\text{SiO}_2$ is increased when the temperature is raised. The above compounds are stable as the temperature is lowered. For the other compounds except $2\text{FeO}\cdot\text{SiO}$, the reaction is raised to the only right between 1600K and 2500K. Especially, $\text{CaO}\cdot\text{SiO}_2$, $2\text{CaO}\cdot\text{SiO}_2$ is a very stable compound, the reaction is almost raised irreversibly. $2\text{FeO}\cdot\text{SiO}$, $\text{FeO}\cdot\text{SiO}$ is an unstable compound and the reaction between 1600K and 2500K is raised to the left (dissociation orientation). $\text{CaO}\cdot\text{SiO}_2$ is stablest in the products of complex deoxidation and the order for the stability is $2\text{CaO}\cdot\text{SiO}_2$, $\text{MnO}\cdot\text{SiO}_2$, $2\text{MnO}\cdot\text{SiO}_2$, $2\text{FeO}\cdot\text{SiO}$.

The melting point and density in products of complex deoxidation

Understanding the melting point and density of complex deoxidation products is crucial for optimizing the welding process, as these properties influence the behavior of slag and inclusions during welding. The study examines several key deoxidation products formed in acid-family welding electrodes, including $\text{CaO}\cdot\text{SiO}_2$, $2\text{CaO}\cdot\text{SiO}_2$, $\text{MnO}\cdot\text{SiO}_2$, $2\text{MnO}\cdot\text{SiO}_2$, and $2\text{FeO}\cdot\text{SiO}_2$ [17]. The melting point of these compounds affects their stability and removal during the welding process. For instance, $\text{CaO}\cdot\text{SiO}_2$ and $2\text{CaO}\cdot\text{SiO}_2$ have higher melting points (1817 K and 2403 K, respectively), making them potential non-metallic inclusions that remain in the

weld. In contrast, $2\text{FeO}\cdot\text{SiO}_2$ has the lowest melting point (1478 K), indicating it may be more easily removed as slag. Density also plays a significant role in the behavior of deoxidation products. Higher density compounds, like $2\text{FeO}\cdot\text{SiO}_2$ (4300 kg/m^3), are more challenging to remove, as they tend to settle in the weld pool [18]. Conversely, $\text{CaO}\cdot\text{SiO}_2$ has a lower density (2620 kg/m^3), which may facilitate its removal. The study concludes that $\text{MnO}\cdot\text{SiO}_2$, with a melting point of 1564 K and a density of 3150 kg/m^3 , offers a balanced combination of properties, making it an effective deoxidation product. Its relatively low melting point (Table 2) and moderate density allow for efficient removal, minimizing inclusions and improving weld quality [19].

Table 2. the melting point and density in products of complex deoxidation.

products of complex deoxidation	melting point,K	density, kg/ m^3	formation rate
$\text{CaO}\cdot\text{SiO}_2$	1817	2620	48:52
$2\text{CaO}\cdot\text{SiO}_2$	2403	2820	65:35
$\text{MnO}\cdot\text{SiO}_2$	1564	3150	54:46
$2\text{MnO}\cdot\text{SiO}_2$	1618	3750	70:30
$2\text{FeO}\cdot\text{SiO}_2$	1478	4300	71:29

The experiment and analysis

For experiment ,the amount of ferromanganese and ferrosilicon for deoxidizer are respectively changed to 10-14% and 4~8%.

On the above- mentioned, we have made the welding electrodes that are 9 in the composition kind and performed the AC welding under welding current 250A, arc voltage 28V, weld rate 10m/h in weld condition.

After welding, we have measured the amount of oxygen from the gas analyzer (EHGA-1300 HORIBA), picking the chip from deposited metal and performing vacuum melting.

The result from the experiment is same as table 3 and figure 1.

Table 3. The amount of oxygen to change of ferromanganese and ferrosilicon (experiment analysis), %

ferrosilicon, % \ ferromanganese, %	4	6	8
10	0.040	0.039	0.050
12	0.038	0.035	0.040
14	0.035	0.030	0.030

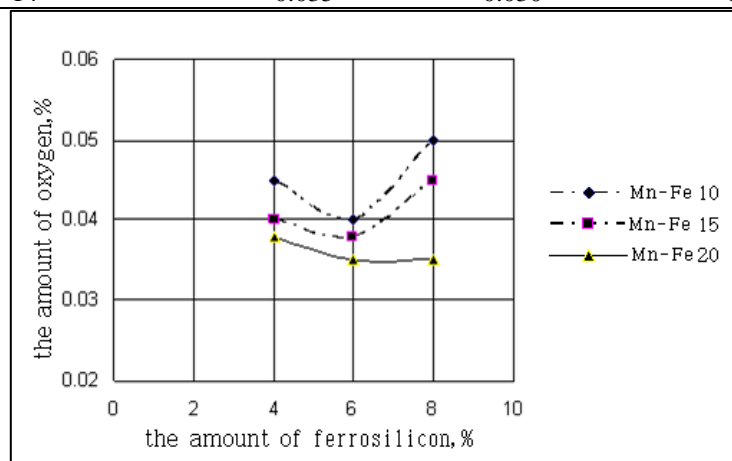


Figure 1. The amount of oxygen to change of ferromanganese and ferrosilicon when complex deoxidation is performed (xperiment analysis).

We have calculated the amount of oxygen at 2000k to analysis the experimental result.

The result from formula (3) is same as table 4 and figure 2.

Table 4. The amount of oxygen when complex deoxidation is performed with ferromanganese and ferrosilicon (calculation).

	ferrosilicon,%	4	6	8
ferromanganese,%	10	0.044	0.042	0.043
12	0.043	0.041	0.042	
14	0.041	0.039	0.038	

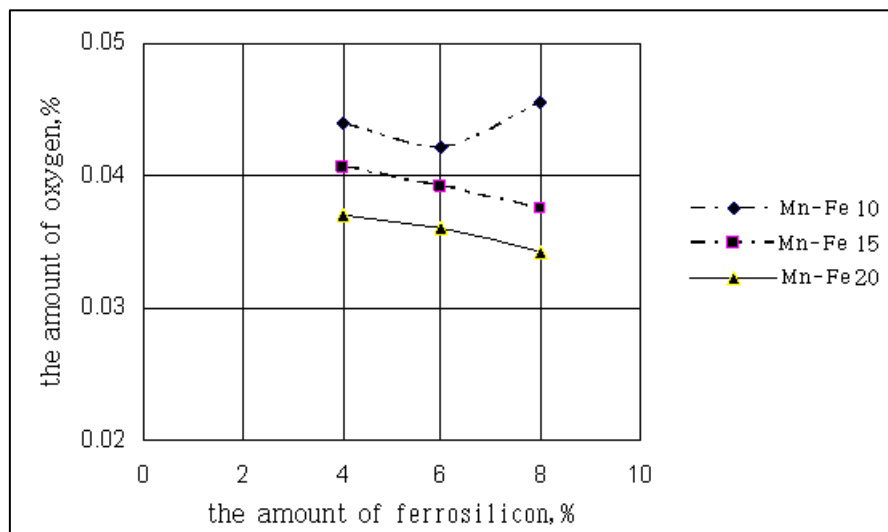
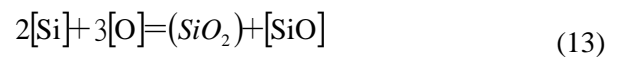


Figure 2. The amount of oxygen to change for the amount of ferromanganese and ferrosilicon when complex deoxidation is performed (calculation).

The amount of oxygen in the weld pool is decreased when the amount of ferromanganese is increased by 10% - 20%.

The amount of oxygen is increased when the amount of ferrosilicon is increased more than 6% if one of ferromanganese is less than 14%.

The reason is as follows.



As you know from (3-25), the amount of oxygen in weld pool is increased when the amount of ferrosilicon is increased more than 6%, forming $[SiO]$ which is complex deoxidation dissolved in weld pool.

The amount of oxygen is decreased in about 0.001-0.003% in comparison with the calculation result.

From the purpose of decreasing the amount of ferromanganese, to decrease the amount of oxygen when the amount of ferromanganese is below 15%, it is necessary that the amount of ferrosilicon is below 6%.

As you know from the above formula, the amount of oxygen in weld pool is increased when the amount of ferrosilicon is increased more than 4%, forming $[SiO]$ which is complex deoxidation dissolved in weld pool.

4 Conclusion

This study demonstrates that complex deoxidation using a combination of ferromanganese and ferrosilicon significantly improves the deoxidation efficiency in acid-family welding electrodes. By optimizing the deoxidizer composition to 12% ferromanganese and 4% ferrosilicon, the oxygen content in the weld pool is reduced more effectively than with ferromanganese alone. The formation of stable deoxidation products, such as $\text{MnO}\cdot\text{SiO}_2$, which has a favorable melting point and density, contributes to enhanced weld quality by minimizing non-metallic inclusions. This approach not only decreases the oxygen levels but also improves the mechanical properties of the weld. The findings highlight the greater influence of ferrosilicon in the deoxidation process, as it predominantly participates in forming deoxidation products, while some manganese remains in the deposited metal. These insights provide a scientific basis for developing more efficient welding processes and improving material performance in industrial applications. This conclusion succinctly summarizes the key findings and implications of the study.

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6 Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper. All authors have approved the manuscript and agree with its submission to the journal. The research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest. These sections are crafted to align with the standards of reputable international journals, ensuring clarity and transparency in the publication process.

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