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A QUANTITATIVE ANALYSIS OF THE EFFECTS OF TIC AND CR ADDITION LEVELS ON THE PERFORMANCE OF NI60 ALLOY COATINGS

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Abstract

In China, Q235 steel is commonly used for the fabrication of soil-engaging components in agricultural machinery. This study utilized laser cladding technology to prepare composite coatings on Q235 steel, examining the effects of varying TiC and Cr content within Ni60 alloy coatings on hardness, wear resistance, and corrosion resistance. The results revealed that at a TiC addition of 40%, the coating's hardness increased approximately 6.6 times compared to the substrate, significantly enhancing wear resistance with a 67% reduction in wear loss. Meanwhile, adding 20% Cr maximized corrosion resistance, reducing corrosion weight loss by 52%. However, excessively high concentrations of TiC or Cr led to increased porosity and a decline in surface quality. These findings provide crucial guidance for optimizing coating materials used in agricultural machinery, particularly in selecting appropriate additive proportions to achieve optimal comprehensive performance.

Keywords: Composite coatings, Corrosion resistance, Hardness, Laser cladding, Wear resistance.

1. Introduction

The issue of steel wear is a global challenge, with wear-related losses accounting for approximately 10% of total global steel production annually. Laser cladding, a surface engineering technique utilizing high-energy laser beams to deposit coating materials onto a metallic substrate and rapidly solidifying to form a metallurgical bond [1], has emerged as a cost-effective solution. This technology not only enables repair and surface enhancement but also offers advantages such as rapid cooling, minimal thermal deformation, few microstructural defects, and high bonding strength between the cladding layer and the substrate, which significantly extend the service life of steel, reduce production costs, and minimize energy wastage [2, 3].

Carbide ceramics, bonded by strong covalent bonds, exhibit high melting points, hardness, strength, and chemical stability, making them ideal for reinforcing metallic substrates. These properties enhance the overall performance of composites in extreme conditions, such as high temperatures, oxidation, vibration, fatigue, temperature fluctuations, and erosion [4]. For instance, Wang et al. [5] utilized laser cladding to produce Ni60A/WC composite coatings on 65Mn steel rotary tiller blades, reducing wear by 63% compared to conventional blades.

Similarly, Demin et al. [6] observed that increasing the TiC content in TiC/Ni composite coatings (with TiC mass fractions of 10%, 20%, and 30%) significantly enhanced the coatings' density, grain size, and average hardness. Furthermore, Jinlong et al. [7] demonstrated that the synergistic effect of dispersion strengthening from TiC and solid solution strengthening from TiC dissolving into the Ni matrix increased with TiC content, progressively enhancing the hardness of the coatings as the TiC percentage rose (0%, 10%, 20%, 30%).

Wear often coincides with corrosion, particularly in agricultural machinery, where soil-engaging components must withstand both. Adding Cr to the process can significantly improve the corrosion resistance of metallic materials. For example, Liu et al. [8] used vacuum liquid-phase sintering to prepare Mo2FeB2-based metal ceramics, observing that increasing Cr content (from 0% to 11% by mass) progressively enhanced corrosion resistance. Similarly, Hung et al. [9] reported positive effects of Cr on improving the corrosion resistance of metal coatings.

Most studies on laser cladding powder compositions limit the additive phase to below 30% [6-8, 10], as higher amounts may reduce the coating's toughness and plasticity [11]. This is due to the rapid heating and cooling during the process, which induces thermal stresses and volumetric shrinkage [11]. However, the effects of higher additive quantities have been less explored.

The objective of this study is to investigate the effects of varying TiC and Cr contents (ranging from 0% to 100%, incrementally increased by 20%) on the hardness, wear resistance, and corrosion resistance of Ni60 alloy coatings produced by laser cladding technology. Q235 steel, a material commonly used for agricultural machinery manufacturing in China, was selected as the substrate [12].

The research aims to provide a comprehensive understanding of how the different proportions of TiC and Cr affect the performance of the coatings, particularly in improving the wear resistance of agricultural machinery components, where high wear and corrosion resistance are crucial for extending service life and reducing maintenance costs.

2. Materials and Methods

The substrate was machined into samples measuring 50 mm × 40 mm × 10 mm. Prior to the experiments, the substrate surfaces were polished to remove oxide layers using sandpapers with grit sizes of 180, 400, and 800. Subsequently, the samples were cleaned in an ultrasonic cleaner for 10 minutes and dried before being stored in airtight containers for further use [13].

The powders used in this study included Ni60 alloy powder, TiC powder, and Cr powder, all provided by Hebei Jincaisheng Special Metal Materials Co., Ltd. (China). Both TiC and Cr powders had purities greater than 99.9%. The main components of the substrate (Q235) and Ni60 alloy powder are listed in Table 1.

Table 1. Composition of Q235 and Ni60 powders (in weight %).

	C	Cr	Si	Mn	B	P	S	Ni	Fe
Substrate	0.22		0.35	1.4		<0.05	<0.05		Bal.
Ni60	0.8	16	4		3.2			Bal.	15

Firstly, based on the experimental design for the coating preparation as shown in Table 2, an electronic balance with a precision of 1 mg was used to measure the required amounts of powder. Subsequently, the powders were uniformly mixed using an all-directional planetary ball mill (produced by Changsha Tianpao Powder Technology Co., Ltd., model QXQM-4L).

Zirconia ceramic balls were used as milling media, and the milling jar was made of stainless steel lined with hard polymer to prevent contamination. Prior to milling, the jar was purged with argon gas of 99.99% purity to prevent oxidation. Milling parameters were set as follows: a ball-to-powder ratio of 3:1, a speed of 300 rpm, and a duration of 3 hours. Finally, the mixed powders were dried in an oven at 105°C for 6 hours to obtain the cladding powder raw materials [14].

Table 2. Coating composition design (in weight %).

No.	TiC	Cr	Ni60	No.	TiC	Cr	Ni60
1	0	0	0	**7**	100	0	0
2	0	0	100	**8**	0	20	80
3	20	0	80	**9**	0	40	60
4	40	0	60	**10**	0	60	40
5	60	0	40	**11**	0	80	20
6	80	0	20	**12**	0	100	0

The coatings were applied using a JSD-3000W laser processing machine (manufactured by Jiangsu Zhiyuan Laser Technology Co., Ltd., China) on Q235 substrates using a synchronous powder feeding technique. Process parameters were set as follows: laser power at 2400 W, defocus distance of 12 mm, spot diameter of 2 mm, scanning speed of 420 mm/min, and an overlap rate of 40%. High-purity argon gas was used as a shielding gas to prevent oxidation at high temperatures, with a flow rate of 5 L/min [15].

After processing, the samples were cut into 10 mm × 10 mm pieces using an EDM wire cutting machine. The samples were then sequentially sanded, dried in an oven, and prepared for subsequent experiments. The hardness of the substrate and coating was measured using a micro Vickers hardness tester (produced by Beijing Epoch

Technology Co., Ltd., China, model: TMVS-1), with a load of 300 g and a dwell time of 15 seconds. Hardness measurements were taken from the top of the coating downwards every 0.2 mm and horizontally at three points to average the values[16].

Wear tests were conducted using a ball-on-disc wear testing machine (produced by Shandong Zhongyi Instrument Co., Ltd., China, model: MMU-10). The counterface material was GCr15 bearing steel balls with a diameter of 6 mm. The test settings included a load of 50 N, a friction radius of 10 mm, a speed of 400 rpm, and a duration of 40 minutes.

The mass of each sample was measured before and after the wear test to calculate the wear loss, which assessed the wear resistance of the samples. To ensure accuracy, each sample was cleaned using an ultrasonic cleaner and dried before being weighed three times and the measurements recorded. The coefficient of friction was continuously recorded by the equipment and exported after the test[17].

The corrosion tests were performed using a static method, with the corrosive medium prepared from a mixture of 98% nitric acid and 35% hydrochloric acid in a 1:1 ratio, diluted with distilled water to a concentration of 15% (acid solution: distilled water ratio of 15:85). The non-coated faces of the samples were sealed with corrosion-resistant glue, exposing only the coated surface. Each sample was immersed in the corrosive solution.

Samples were removed every two hours, rinsed with anhydrous ethanol, dried, and weighed; the corrosion test concluded after 10 hours. The corrosion resistance was evaluated based on the average weight loss due to corrosion [7]. All measurements were performed in triplicate under identical conditions to ensure the repeatability and reliability of the results.

This study hypothesizes that the addition of TiC and Cr significantly affects the forming quality, hardness, and wear resistance of Ni60 alloy coatings. In practical applications, while the addition of TiC and Cr enhances wear resistance and hardness, it also presents certain challenges. For agricultural machinery soil-contacting components, the high hardness of TiC improves wear resistance; however, excessive TiC content may cause uneven particle distribution or increased brittleness, particularly under high-load and high-friction conditions, leading to coating delamination or cracking.

The addition of Cr improves corrosion resistance and high-temperature strength, but excessive Cr can induce internal stress, compromise toughness and leading to failure under impact or temperature fluctuations. Agricultural components are subjected to complex external forces and harsh soil conditions, requiring careful optimization of TiC and Cr content to balance wear resistance with good forming quality and sufficient toughness, thus extending component service life.

3. Results and Analysis

3.1. Surface morphology analysis

Figure 1 displays the morphologies of coatings with varying TiC and Cr contents. Sample #1 shows the untreated Q235 steel substrate, which is smooth but has machining marks. Sample #2, with Ni60 powder cladding, has a uniform, dense surface with a few small spherical particles, indicating good quality despite minor imperfections.

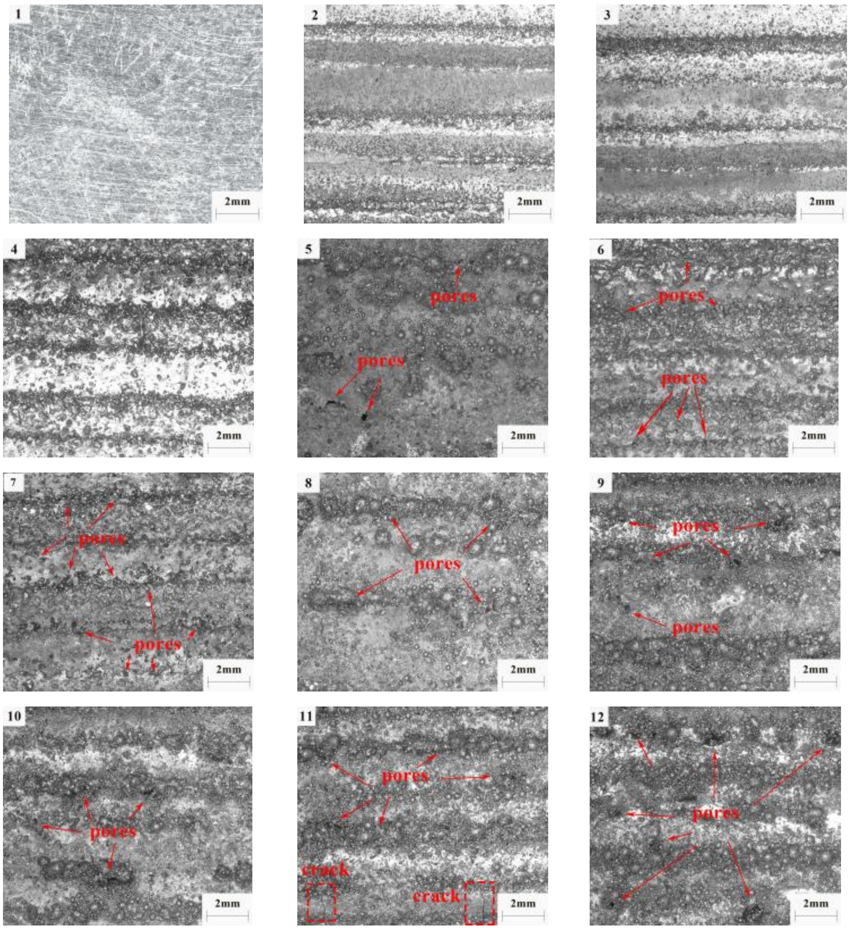

Fig. 1. Morphologies of coatings prepared with varying amounts of TiC and Cr.

Samples #3 to #7 represent TiC additions of 20%, 40%, 60%, 80%, and 100%, respectively. With 20% TiC (sample #3), the coating is uniform with no apparent pores. As TiC content increases to 40% (sample #4), surface roughness increases due to less effective bonding. At 60% TiC (sample #5), porosity increases, and the surface becomes rougher. Higher TiC content (80% and 100%, samples #6 and #7) leads to even greater porosity and roughness, with poor uniformity and lower coating quality. Samples #8 to #12 represent Cr additions of 20%, 40%, 60%, 80%, and 100%. With 20% Cr, the coating shows moderate pores and roughness. As Cr content increases, porosity increases, and surface quality worsens. At 80% and 100% Cr (samples #11 and #12), the coating becomes highly porous and brittle, with cracks forming due to instability during the cladding process.

TiC, as a hard particle, can effectively enhance the coating's hardness, but its high content leads to decreased density and uniformity of the coating, forming more pores and increasing roughness. This is because at high TiC contents, the binding force between particles is insufficient, leading to poor flowability during the cladding process and easy formation of pores.

The addition of Cr can improve the coating's hardness and corrosion resistance, but excessively high Cr contents increase the brittleness of the coating structure. During the cladding process, high Cr contents easily cause stress concentration during cooling, leading to the formation of pores and cracks, significantly reducing the surface quality of the coating [16, 18]. From the perspective of the surface formation quality of the coating, using laser cladding to process wear-resistant coatings, the addition of TiC should not exceed 40%, and the addition of Cr should not exceed 20%.

3.2. Hardness analysis

According to Archard's theory, when the friction load and distance are constant, the amount of wear is inversely proportional to the hardness of the cladding layer; that is, the higher the hardness of the cladding layer, the better its wear resistance [19]. Because hardness testing is relatively quicker and more convenient compared to wear testing, many researchers evaluate the wear resistance of metallic materials by measuring their hardness. Figures 2 and 3 illustrate the trend in hardness variations across all samples.

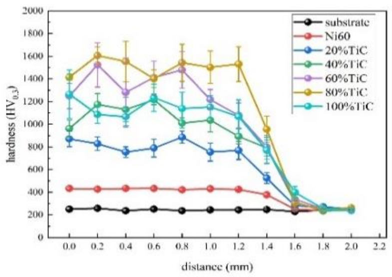

Fig. 2. Impact of TiC content on the hardness of the coating.

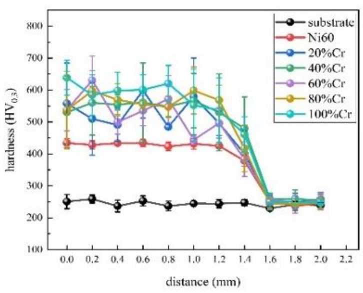

Fig. 3. Effect of Cr content on the hardness of the coating.

From the trend observed in the curve of Fig. 2, it is evident that the substrate has the lowest hardness, while the hardness of the Ni60 alloy coating is slightly higher than that of the substrate, with both showing relatively stable hardness values. The average hardness values for the substrate and Ni60 alloy coating are 244 $HV_{0.3}$ and 375 $HV_{0.3}$, respectively. The addition of TiC powder alone significantly increases the hardness of the composite coating compared to both the substrate and the Ni60 alloy coating. As the TiC content increases up to 80%, the hardness of the coating shows an upward trend; however, further increases in TiC content result in a decrease in hardness.

The peak hardness values for TiC contents of 20%, 40%, 60%, 80%, and 100% are 870 $HV_{0.3}$, 1216 $HV_{0.3}$, 1524 $HV_{0.3}$, 1606 $HV_{0.3}$, and 1266 $HV_{0.3}$, respectively. The hardness of the composite coatings prepared with varying TiC contents remains relatively stable when the measurement depth does not exceed 1.2 mm. Between depths of 1.2 mm and 1.6 mm, a sharp decline in hardness is observed in all coatings. Beyond a depth of 1.6 mm, the hardness values of all samples tend to converge, suggesting that the coating thickness is approximately 1.6 mm.

The increase in composite coating hardness with the addition of TiC powder can be primarily attributed to three factors: first, the high hardness characteristic of TiC reinforcing particles, although some decomposition of TiC particles occurs, a large portion remains within the composite coating, enhancing its strength; second, elements from partially decomposed TiC particles recombine with other components of the coating to form hard phases, contributing to dispersion strengthening by impeding dislocation movement, thus increasing the composite coating's hardness; and third, the introduction of TiC particles refines the Ni60 alloy substrate through grain refinement, enhancing the composite coating's hardness [20].

Figure 3 shows the curve depicting the effect of varying Cr content on the hardness of the coatings. Similar to the addition of TiC powder alone, the hardness of composite coatings prepared with different amounts of Cr powder remains relatively stable when the measurement depth does not exceed 1.2 mm. Between depths of 1.2 mm and 1.6 mm, the hardness of all coatings shows a sharp decline.

Beyond a depth of 1.6 mm, the hardness values of all samples tend to converge. However, a distinct difference is noted in that the addition of Cr powder alone to Ni60 alloy powder results in only a slight increase in hardness relative to the substrate and Ni60 alloy coating, and the magnitude of increase is minimal.

When Cr content varies from 20% to 100%, there is no significant difference in the hardness of the coatings. According to literature, although Cr atoms form metallic bonds with Fe atoms, these bonds possess some covalent characteristics, and the covalent bond properties are relatively strong, making the Cr-Fe metallic bond the strongest. In contrast, the metallic bond between Ni and Fe atoms also features covalent characteristics, but they are weaker than those between Cr and Fe [21]. This might explain why the addition of Cr alone to Ni60 alloy powder does not significantly enhance the coating's hardness.

From the hardness variation curves, it is evident that adding TiC and Cr powders to Ni60 powder affects the coating hardness differently. TiC, as a hard particle, significantly enhances coating hardness, with hardness increasing with the TiC content up to 80%, reaching a peak of 1606 $HV_{0.3}$, which is 6.8 times the hardness of the substrate and 4.3 times that of the Ni60 alloy coating. However, high amounts of TiC reduce the density and uniformity of the coating, leading to increased porosity and roughness, and consequently a reduction in coating hardness.

By comparison, while the addition of Cr can also enhance coating hardness, the effect is not as pronounced as with TiC. The variation in hardness with different Cr contents is small, with increments remaining limited to between 500-700 $HV_{0.3}$ for additions ranging from 20% to 100%. This is because high amounts of Cr tend to cause stress concentration during cooling, leading to the formation of pores and cracks, thus degrading the surface quality. In summary, when processing wear-resistant coatings using laser cladding, to enhance coating hardness, the addition of TiC should not exceed 80%. An addition of Cr over 20% has a negligible impact on hardness. Therefore, the Cr content should be controlled at 20% or less.

3.3. Wear loss and coefficient of friction analysis

Generally, the hardness of metal materials is positively correlated with their wear resistance. However, higher hardness may also indicate greater brittleness. Under impact or cyclic stress, the material's surface is prone to developing micro-defects such as pits and cracks, leading to significant material spalling or detachment [22]. In such cases, the relationship between hardness and wear resistance is not positively correlated. To accurately assess the impact of TiC and Cr addition on the wear resistance of coatings, this study conducted friction wear tests.

Typically, softer metal materials experience adhesive wear during friction wear tests, resulting in higher friction coefficients. Additionally, the density and uniformity of the metal's internal structure also affect the material's friction coefficient. Therefore, evaluating the wear resistance of metal materials requires a comprehensive consideration of both wear loss and friction coefficient [23]. The experimental results are shown in Figs. 4 and 5. The bar graphs display the weight loss due to wear under the same experimental conditions, while the line graphs show the average friction coefficient for each sample under the same conditions.

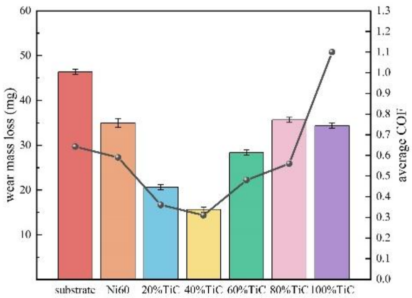

Fig. 4. Impact of TiC content on coating hardness.

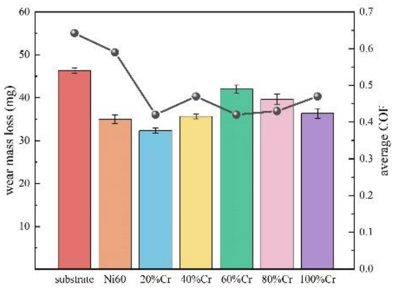

Fig. 5. Effect of Cr content on coating hardness.

From Fig. 4, it is observed that the wear loss for the substrate and Ni60 alloy coating are 46.33 mg and 35 mg, respectively, with average coefficients of friction (COF) of 0.642 and 0.59. After adding TiC powder, the wear resistance of the coating significantly improved, particularly when the TiC content was 20% and 40%, with wear losses dramatically reduced to 20.67 mg and 15.67 mg, respectively. The COF also showed a decreasing trend, with average COF values of 0.36 and 0.31 for coatings with 20% and 40% TiC, respectively.

However, as the TiC content increased further to 60%, the wear loss increased to 28.33 mg, and the average COF rose to 0.48. At TiC contents of 80% and 100%, the wear losses were 35.67 mg and 34.33 mg, respectively, with significant increases in average COF to 0.56 and 1.1. This indicates that a moderate addition of TiC can significantly enhance the wear resistance of the coating, but excessive TiC content leads to a significant increase in the COF, thereby affecting the wear resistance adversely.

Figure 5 shows the effects of adding different amounts of Cr on the hardness of the coatings. After adding Cr powder, the wear resistance of the coatings slightly improved compared to the substrate. However, compared to coatings prepared with Ni60 alone, there was no clear trend in wear resistance after adding Cr. With Cr contents of 20% and 40%, wear losses were 32.33 mg and 35.67 mg, respectively, with average COF values of 0.42 and 0.47. When Cr content increased to 60%, the wear loss rose to 42 mg, but the average COF remained at 0.42. At Cr contents of 80% and 100%, the wear losses were 39.67 mg and 36.33 mg, respectively, with average COF values of 0.43 and

0.47. This suggests that the addition of Cr did not actively enhance the wear resistance of the Ni60 alloy coating.

The experimental results indicate that moderate addition of TiC can enhance the wear resistance of Ni60 alloy coatings, but the effect is closely related to the amount added. The best wear resistance of the coating, with the lowest wear loss and COF, occurs at TiC contents of 20% and 40%. When the addition of Cr exceeds 20%, it does not actively contribute to enhancing the wear resistance of Ni60 alloy coatings. From a wear resistance perspective, the addition of TiC should be kept below 80%. When Cr is added beyond 20%, it does not significantly affect the wear resistance of Ni60 alloy coatings. Therefore, if the addition of Cr is necessary, it should be controlled at 20% or less.

3.4. Corrosion resistance analysis

For agricultural soil-engaging components, failure is not only caused by friction wear but also by corrosion wear. Corrosion wear refers to the phenomenon where the surface of the components chemically or electrochemically reacts with moisture, pH levels, and organic matter in the soil, leading to the formation of corrosion products on the component's surface, which subsequently undergoes mechanical abrasive wear and spalling [24]. In this study, the static immersion corrosion method was employed to investigate the corrosion resistance of coatings prepared by adding different contents of TiC and Cr to Ni60 alloy powder. The experimental results are shown in Figs. 6 and 7.

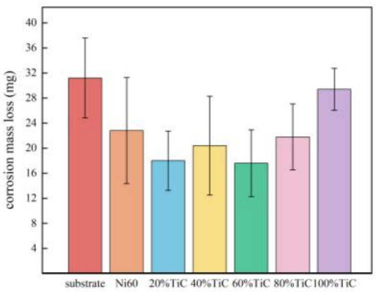

Fig. 6. Impact of TiC content on the corrosion resistance of the coating.

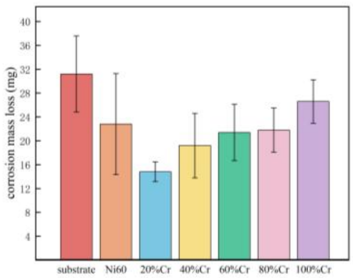

Fig. 7. Effect of Cr content on the corrosion resistance of the coating.

Figure 6 shows the impact of different TiC contents in Ni60 alloy powder on the corrosion resistance of the coating, with the vertical axis representing the average weight loss every 2 hours. The highest corrosion weight loss was seen in the substrate, with an average of 31.2 mg every 2 hours, indicating low corrosion resistance. The coating made from Ni60 alloy powder showed moderate corrosion resistance, with a corresponding weight loss of 22.8 mg.

As the TiC content increased to 20%, the coating's weight loss decreased to 18 mg, demonstrating a significant improvement in corrosion resistance. At TiC contents of 40% and 60%, the weight loss fluctuated slightly, recording 20.4 mg and 17.6 mg, respectively. However, when TiC content continued to increase to 80% and 100%, the weight loss again increased, reaching 21.8 mg and 29.4 mg, respectively.

This suggests that excessive TiC content may have a negative impact on the overall corrosion resistance of the coating. With TiC additions reaching 60% or higher, the coating developed numerous pores, as shown in Fig. 6. Therefore, when the TiC content exceeds 40%, the wear resistance of the coating tends to decline.

Figure 7 illustrates the effects of adding different amounts of Cr on the coating's corrosion resistance, with the vertical axis showing the average weight loss every 2 hours. Adding 20% Cr significantly improved the coating's corrosion resistance, reducing the corrosion weight loss to the lowest value of 14.8 mg. As the Cr content increased to 40%, 60%, and 80%, the corrosion weight loss recorded was 19.2 mg, 21.4 mg, and 21.8 mg, respectively, showing a slight decline in corrosion resistance.

When the Cr content reached 100%, the weight loss increased to 26.6 mg, indicating that excessively high Cr content might not be beneficial for enhancing corrosion resistance. From Fig. 7, it can be seen that with Cr additions of 20% and above, the surface quality of the coating was poor. The coating's surface exhibited defects such as pores or cracks. As the Cr content increased, the surface quality of the coating tended to worsen. Therefore, as the Cr content in the coating increased, the corrosion resistance showed a declining trend.

Combining the data analysis from both figures, it can be concluded that adding TiC to Ni60 alloy can improve its corrosion resistance, but there is an optimal amount of addition; exceeding this amount might reduce corrosion resistance. The optimal addition amount of TiC is below 40%. Meanwhile, as the Cr content in the coating increases, the corrosion resistance tends to decline.

Therefore, if it is necessary to add Cr to improve performance, the optimal addition amount should be kept at 20% or less. Excessively high addition amounts not only fail to further enhance corrosion resistance but may also lead to a decrease in corrosion resistance due to the coating's unevenness or other microstructural issues.

3.5. Summary analysis

Through analyses of coating surface morphology, hardness, wear resistance, and corrosion resistance, optimal addition amounts for TiC and Cr for each performance indicator have been determined, as shown in Table 3.

Table 3. Optimal addition amounts of TiC and Cr for different indices.

Indicator	Optimal TiC Addition	Optimal Cr Addition
Surface Morphology	Up to 40%	Up to 20%
Hardness	Up to 80%	Up to 20%
Wear Resistance	Up to 40%	Up to 20%
Corrosion Resistance	Below 40%	Up to 20%

From Table 3, it is deduced that when the TiC addition does not exceed 40%, the coating demonstrates good performance in terms of surface morphology, hardness, and wear resistance. Although adding up to 80% TiC in Ni60 alloy does increase the hardness with the increasing content of TiC, in this study, the importance of hardness is less significant than wear resistance. While coatings prepared with 40% TiC exhibit a slight decrease in corrosion resistance compared to those with 20% TiC (with a decrease of only 13%), the overall composite performance is better. Therefore, when preparing composite coatings, it is recommended to keep the TiC content within 40% in Ni60 alloy. ZHAO et al. investigated the effect of WC content on WC-Ni60 spray welded coatings. Their results indicated that as the WC content increased from 10% to 50%, the microhardness of the coating continuously increased.

However, when the WC content exceeded 30%, defects such as porosity became more prevalent in the coating[25]. Similarly, TIAN et al. demonstrated through their study that when the mass fraction of WC in Ni60 alloy exceeded 25%, the coating was prone to the formation of brittle cracks and fatigue cracks[26]. Some scholars enhance the mechanical properties of metal materials by adding Cr [8, 27]. However, based on the experimental findings of this study, if it is necessary to add Cr to the coating composition in Ni60 alloy, the Cr content should be kept at or below 20%. YAO et al. pointed out that when no more than 2.5% of Cr_3C_2 was added to the WC-Ni coating, the coatings exhibited good hardness and friction-wear performance. Correspondingly, the amount of Cr added was equivalent to no more than 2.16% [28].

4. Conclusion

An investigation has been made of the effects of TiC and Cr additions on Ni60 alloy coatings produced by laser cladding on Q235 steel. Some concluding observations are given below.

- TiC addition enhances the hardness of Ni60 coatings by up to 80%, with the best wear resistance observed when the addition is controlled between 20-40%. Beyond this range, the improvement effect declines, indicating the importance of optimizing TiC content.
- Cr addition improves both hardness and corrosion resistance, with the optimal effect at about 20%. However, excessive Cr leads to coating defects and compromises coating quality, highlighting the need for careful composition control and further investigation into the role of intrinsic versus added Cr.
- Economic analysis shows that coating application costs less than 10% of the price of typical agricultural components such as rotary tiller blades, while providing about three times the wear resistance of the substrate. This demonstrates not only substantial economic benefits in agricultural machinery but also broad application potential in other industrial wear environments.

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