The pre-hot dipping effects on the bimetal casting of nitriding steel sleeve into the Al-Si matrix

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Abstract. Steel-aluminum composite material combine the excellent mechanical properties of steel such as high strength and good wear resistance with the advantages of lightweight aluminum for widely using in automobile engine block, gearbox and other car body structures. In this paper, a new process is used to cast the alloy steel sleeve into Al-Si alloy matrix for preparing aluminum engine block with steel cylinder liner. The process consists of three parts: the surface pre-treatment of steel, the hot-dipping melt and solid-liquid casting of steel with aluminum. Generally, the hot dipping melt should have lower melting point than the melting point of aluminum alloy, good temperature oxidation resistance and amount of solid solubility both with steel and aluminum. Giving consideration of such condition and cost, Zn, Al and its alloys are used in present paper for learning the effect of hot dip coating melts on the interface properties of steel/aluminum at different times. After hot dipping, a coating formed on the surface of the steel bushing, which improves its wettability in the aluminum melt and the metallurgical bonding effect of the steel-aluminum interface. The microstructure, phase composition, growth kinetics and hardness distribution of the interface were analyzed by metallographic microscopy, scanning electron microscopy with EDS. The results show that the metallurgical bonding interface of steel/aluminum bimetal casting can be obtained by hot dipping. Hard-brittle diffusion layer produced by dipping pure Al is thicker than that produced by ZL101. Dipping pure zinc produces a dense intermetallic layer of 3-5 um and a large amount of dispersed phase of Al3FeZn5, and the bonding performance of such interface is better than the other two. The interface hardness of steel-aluminum bimetal casting obtained by hot dipping pure Al melt, ZL101 melt and pure Zn melt can reach 563.5HV, 528.3HV and 632.3HV, respectively.

1. Introduction
With the rapid development of science and technology and the continuous improvement of living standards, people's requirements for the performance of materials in all aspects have become higher and higher. In some fields, single materials have been difficult to meet people's needs for production and life. In order to make the application range of materials wider and meet the requirements of different environments, people have developed a variety of materials. Composite materials is a new type of material prepared by combining two or more materials with different physical, chemical, and mechanical properties using a composite method [1]. Composite materials can make use of their respective advantages, avoid their disadvantages, and can greatly improve the overall performance of the material [2]. Nowadays, the demand for light weight of automobiles is rapidly developing,
Aluminum alloy is a kind of lightweight alloy, which has the advantages of light weight, corrosion resistance and so on. It has been widely used in various fields [3]. Due to the poor mechanical properties of aluminum alloy, its application range is limited. Steel has excellent properties such as high strength, high temperature resistance, etc [4]. Combining steel and aluminum to prepare steel/aluminum composite materials can meet the requirement of light weight, which makes the application of the material more promising. Bimetal composite materials have been widely used in automobile manufacturing, shipbuilding, mechanical processing, aerospace and other fields [5].

According to the state of the metal in the composite process, the preparation process of the bimetal composite material is divided into three types: solid-solid composite, solid-liquid composite, and liquid-liquid composite [6]. The preparation process of the solid-solid composite method is relatively complicated, and the performance of the materials to be connected is relatively high. The prepared bimetal material can only achieve mechanical bonding, and cannot achieve the effect of metallurgical bonding [7]. The liquid-liquid composite method has high requirements on equipment, and it is difficult to control the flow of two metals during the pouring process. The cost of the liquid-liquid composite method is high and the process is complicated, so it is difficult to be widely used in actual production [8]. The solid-liquid composite method is a method in which a liquid alloy is cast on a solid metal, and metallurgical bonding is achieved by diffusion between atoms. The prepared bimetal has high bonding performance. The solid-liquid composite method is widely used in practical production because of its low requirements for materials and simple process. It is the most common process for preparing steel/ aluminum composite materials at present [9]. However, in the preparation process, the physical and chemical properties of steel and aluminum are quite different [10], and the aluminum liquid solidifies rapidly on the steel matrix, the diffusion time between Fe and Al atoms is short, so the metallurgical bonding effect is poor, which limits the development and application of steel/aluminum bimetal. In addition, the molten aluminum alloy is easily oxidized during pouring, which reduces its wettability to the steel surface, hinders the diffusion of atoms [11], and reduces the bonding performance of the interface. Therefore, coating pretreatment on the substrate is generally used to improve the bonding performance of the interface in the production. The usual pretreatment processes are divided into hot dip plating and electroplating [12]. The Swiss scientist Papis K.J.M. et al [13]. Pre-plated Zn on the surface of the steel, and then cast molten aluminum to prepare the steel/aluminum composite. The study found that the steel/aluminum composite interface prepared by pre-plating Zn can achieve good metallurgical bonding. However, the cost of the plating process is high and the operation is relatively complicated. German Spring H. et al [14]. Carried out solid-liquid composite of low carbon steel with pure aluminum and aluminum-silicon alloys, and studied the effect of Si on the bonding performance of the steel/aluminum interface, and concluded that Si element can inhibit the growth of diffusion layer at the steel/aluminum interface. Chinese scholars Chen Guoshi and other scholars [15] prepared the HT250/ZL101A bimetal composite cylinder block by hot dip plating and then pouring. The microstructure of the bimetal interface under different preparation processes was studied, and the best preparation process of bimetal was that cast iron was dipped in aluminum alloy melt at 700 °C for 10 minutes and then poured, but the mechanical properties of the bimetal interface and the growth kinetics of the diffusion layer were not studied. Therefore, in this paper, 38CrMoA alloy steel is used as engine cylinder liner and ZL702A is used as engine cylinder. Through hot-dip pretreatment of steel, the steel matrix is prevented from being oxidized, the wettability of aluminum melt to steel is improved, and the adhesion of interface is enhanced. The microstructure, phase composition, growth kinetics of compound layer and distribution of microhardness of interface are studied.

2. Experimental materials and methods

2.1. Experimental Materials
The experimental materials used 38CrMoA alloy steel, ZL702A; other materials: industrial pure aluminum, ZL101, pure zinc; the chemical composition of the steel matrix and aluminum alloy are
shown in table 1, table 2.

**Table 1.** Chemical composition of 38CrMoA alloy steel.

| Element | C  | Si | Mn  | Cr  | Mo  | Al  | Fe  |
|---------|----|----|-----|-----|-----|-----|-----|
| Content (W/%) | 0.35~0.42 | 0.2~0.45 | 0.3~0.6 | 1.35~1.65 | 0.15~0.25 | 0.7~1.1 | Balance |

| Element | Si  | Cu  | Mg  | Mn  | Ti  | B  | Zr  | Al  |
|---------|-----|-----|-----|-----|-----|----|-----|-----|
| Content (W/%) | 6.0~8.0 | 1.3~2.0 | 0.2~0.4 | 0.15~0.25 | 0.05~0.15 | 0.02~0.05 | 0.05~0.1 | Balance |

2.2. Experimental process

In this paper, the solid-liquid composite method is used to prepare bimetal composites. The microstructure and bonding properties of the steel/aluminum interface are analyzed, and the effects of different processes on interface bonding are studied. The experiment is divided into two parts: sample preparation and analysis. Because there may be impurities on the surface of the steel substrate, in order to avoid the compounds generated by the reaction between these impurities and the aluminum alloy during the casting of the molten aluminum alloy hinder the diffusion of atoms, reduce the wettability of the aluminum liquid to the steel substrate, and reduce the interface bonding effect, it is necessary to clean the surface of steel matrix before pouring. The steel/aluminum bimetal composite process is divided into: steel substrate surface cleaning, hot-dip plating, hot dip plating (see table 3 for parameters), steel/aluminum composite process, steel/aluminum sample preparation, detection analysis, and so on.

The composite bimetal is made into metallographic samples by wire cutting. The samples are ground on sandpaper of 180 # to 2000 #, and then polished, etched, and dried. SEM is used to observe the microstructure and morphology of the steel/aluminum bonding zone, analyze the thickness, interface and matrix morphology of the steel/aluminum diffusion layer under different processes. And EDS is used to analyze the distribution and content of elements in the bonding zone. The microhardness of the diffusion layer and the matrix is measured by micro-hardness tester. The width of bonding zone and microhardness were observed under different processes.

| Hot dip plating temperature/℃ | Hot-dip melt | Hot-dip time/min |
|-------------------------------|--------------|-----------------|
| 720±10                        | Pure aluminum| 5，10，15，20    |
| 720±10                        | ZL101        | 5，10，15，20    |
| 450±10                        | Pure zinc    | 5，10，15，20    |

3. Experimental results

3.1. Effect of hot-dip aluminum on steel / aluminum interface bonding properties

3.1.1. Microstructure analysis of steel / aluminum interface after hot-dip pure aluminum plating. The solid-liquid composite process of steel / aluminum bimetal is mainly through the diffusion reaction between the steel matrix and the molten aluminum alloy to form a diffusion layer mainly composed of intermetallic compounds, so as to achieve the metallurgical bonding of materials. Figure 1 shows the microstructure of the steel / aluminum bimetal interface at different hot-dip plating times. Figure (a), (b), (c) and (d) are the interface morphology formed by pouring after the steel matrix hot-dip pure aluminum melt for 5min, 10min, 15min and 20min respectively. As shown in Figure (a), when the hot-
dip time is 5 minutes, a metallurgical bonding layer of about 5 μm is formed on the interface, but there are still gaps on the interface, and the metallurgical bonding effect is poor. The short time of hot-dip will result in the phenomenon of missing plating on the steel matrix and poor interface bonding, which will reduce the mechanical properties of bimetal interface; As shown in figure (b), when the hot-dip time is 10 min, the interface is basically seamless, metallurgical bonding is good, and the thickness of diffusion layer is about 15 μm; As shown in figure (c), when the hot-dip time is 15 minutes, the thickness of the diffusion layer becomes wider, about 23 μm. It also can be seen from the figure (c) that the morphology of the connection between the diffusion layer and the steel matrix, aluminum alloy is basically flat; As shown in figure (d), when the hot-dip time is 20 min, the width of diffusion layer basically changes little, about 26 μm. The results show that the thickness of the diffusion layer increases with the extension of the hot-dip time. Because with the extension of the time of the hot-dip time, the diffusion between Fe atoms and Al atoms is more sufficient, so that the thickness of the diffusion layer increases. When the hot-dip time reaches a certain value, the thickness of the diffusion layer does not change much.

![Figure 1](image-url)

**Figure 1.** Microstructure of the steel / aluminum bimetal interface at different hot dip times.

(a) 5min (b) 10min (c) 15min (d) 20min

3.1.2. *Composition analysis of steel / aluminum interface after hot-dip pure aluminum.* Figure 2 is SEM image of the steel / aluminum interface after hot-dip pure aluminum melt for 15 minutes. It can be observed that a continuous diffusion layer of about 23 μm is formed at the interface. The diffusion layer is flat on the side connected to the steel matrix, and uneven on the side connected to the aluminum alloy. The composition of each phase on the interface is analyzed by EDS. The composition
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of each point is shown in table 4. There is a large amount of Fe and Cr element at point 1, which is inferred to be steel matrix. Point 2 contains a large amount of Al and Fe element, and a small amount of Cr element, Cr element has a substitution effect on Fe element. The atomic ratio of Al: (Fe, Cr) is 2.67: 1. According to the Fe-Al phase diagram, it is known that as the Al content in Fe increases during the reaction between iron and aluminum, intermetallic compounds such as FeAl3, Fe2Al5, FeAl2, FeAl, and Fe3Al are successively formed. Among them, FeAl3 and Fe2A15 have the lowest free energy during the formation. Therefore, when steel and aluminum react, FeAl3 and Fe2A15 are most likely to be formed, so the phase is Fe2A15. Since the aluminum alloy solidifies faster during casting and the atomic diffusion distance is short, the element content of the diffusion layer is basically the same as that before casting, and there is almost no Si element; Point 3 mainly contains Al element and Si element, and it is inferred that it is cast Aluminum alloy.

![Figure 2. SEM of steel / aluminum interface after hot-dip pure aluminum melt for 15 min.](image)

**Table 4.** Composition analysis of each point on the steel / aluminum interface after hot-dip pure aluminum melt treatment for 15 minutes.

| Point | chemical composition (at.%) |
|-------|-----------------------------|
|       | Al  | Fe  | Cr  | Si  |
| 1     | 3.17 | 69.52 | 19.27 | —   |
| 2     | 72.69 | 21.12 | 6.19  | —   |
| 3     | 65.93 | —   | —   | 34.07 |

3.1.3. Microhardness analysis of steel / aluminum interface after hot-dip pure aluminum. The mechanical properties of the steel / aluminum bimetal composite interface are greatly affected by the microstructure. In order to further study the effect of different hot dip treatment on the interface, microhardness tests are performed in the vertical direction of the interface of each sample, and the results are shown shown in Figure 3. From left to right in the figure, it is divided into the microhardness of aluminum alloy, diffusion layer and steel matrix. It can be seen that the
The microhardness of the steel matrix is between 290HV ~ 410HV; the microhardness of the diffusion layer is between 450HV ~ 570HV, because the intermetallic compounds formed by the reaction between Fe and Al are hard and brittle phases; the microhardness on the aluminum matrix side is low, between 58HV ~ 90HV. The microhardness of the steel / aluminum bimetal interface diffusion layer formed after the sample is hot-dip in pure aluminum melt for 20min is the highest, because the hot-dip time is longer and the diffusion between the Fe and Al is more sufficient. Uniform distribution of intermetallic compound is formed.

![Microhardness distribution of steel / aluminum interface under different hot-dip time.](image)

**Figure 3.** Microhardness distribution of steel / aluminum interface under different hot-dip time.

3.1.4. Growth kinetics of steel / aluminum interface diffusion layer after hot-dip aluminizing

Temperature and time are the main factors that affect the growth state of bimetal composite interface diffusion layer. Temperature mainly affects the diffusion rate between atoms. Time mainly affects the distance of atom diffusion. Temperature and time determine the growth of diffusion layer. Figure 4 shows the thickness change of the steel / aluminum composite diffusion layer under different hot-dip times. It can be seen that as the hot-dip time increases, the thickness of the diffusion layer increases continuously. When the hot-dip time reaches a certain value, the thickness of diffusion layer basically does not change much. Through the dynamic analysis of the diffusion layer growth, the growth law of the diffusion layer is obtained.

![Variation curve of diffusion layer thickness under different hot dip time.](image)

**Figure 4.** Variation curve of diffusion layer thickness under different hot dip time.
When the hot-dip temperature is constant, the relationship between the thickness of diffusion layer and the hot-dip time can be expressed by the following formula without considering other factors:

$$\Delta x = kt^n$$  \hspace{1cm} (1)

Among them, $\Delta x$ represents the thickness of the diffusion layer, $t$ is the hot dip plating time, $k$ is the reaction rate, and $n$ is the reaction kinetic index.

Take the natural logarithm of both sides of formula (1) to get formula (2). The slope of $\ln \Delta x$ and $\ln t$ is calculated as the kinetic index $n$ of the reaction layer. At the same time, the intercept of the straight line is the logarithm of the reaction rate, which is $\ln k$.

$$\ln \Delta x = n \ln t + \ln k$$  \hspace{1cm} (2)

The thickness of interface diffusion layer and its corresponding time under different hot-dip time are substituted into the formula (2), and linear fitting is carried out to obtain the relationship between $\ln \Delta x$ and $\ln t$, as shown in figure 5.

**Figure 5.** Relationship between $\ln \Delta x$ and $\ln t$.

After fitting, the figure shows $n = 0.56501$; $\ln k = -14.40029$. By substituting the data into (3), the function relationship between $\ln \Delta x$ and $\ln t$ of diffusion layer is obtained:

$$\ln \Delta x = 0.56501 \ln t - 14.40029$$  \hspace{1cm} (3)

By finishing formula (3), the growth kinetic equation of the thickness of the steel/aluminum bimetal interface diffusion layer $\Delta x$ with the hot-dip time $t$ is obtained:

$$\Delta x = 5.57 \times 10^{-7} t^{0.56501}$$  \hspace{1cm} (4)

Among them, the kinetic index $n = 0.56501$, and the reaction rate $k = 5.57 \times 10^{-7}$. According to the classical kinetic theory, the growth mechanism of the diffusion layer can be determined according to the kinetic index $n$. When the $n$ is close to 0.25, the growth of diffusion layer is mainly controlled by grain boundary diffusion; when the $n$ is close to 0.5, the growth of diffusion layer is mainly controlled by bulk diffusion. It can be known from formula (4) that $n$ is close to 0.5, which indicates that the thickness of the diffusion layer is proportional to the square root of the hot dip time. The diffusion layer basically conforms to the parabolic growth law. The growth of diffusion layer is controlled by bulk diffusion (intragranular diffusion), that is to say, Fe and Al elements can overcome the lattice resistance of primary intermetallics by displacement.

Figure 6 is the SEM diagram of the steel / aluminum bimetal interface formed by pouring the steel matrix after hot dip in molten ZL101 for 15min. It can be observed that the average thickness of
diffusion layer is 18 μm, the side of diffusion layer connected with steel matrix is relatively flat, and the side connected with aluminum alloy is zigzag. The compositions of each point on the interface are analyzed by EDS, and the compositions of each point are shown in table 5. A large amount of Fe and Al elements, as well as a small amount of Cr and Si elements exist at points 1 and 2, and the atomic ratio is similar to that of Fe2Al5. It is speculated that the phase layer is Fe2Al5 phase based on the phase diagram; Point 3 contains a large amount of Al, Fe, Si, and a small amount of Cr. The atomic ratio is Al: Fe: Si = 5: 1: 1. According to the Fe-Al-Si ternary phase diagram, it can be seen that when the Si content is 6-8%, as the Fe content in the Al solution increases, intermetallic compounds such as Al5FeSi, Al8Fe2Si, and FeAl3 will appear successively, so the phase is Al5FeSi; The point 4 is a lamellar structure, According to the analysis of the composition and phase diagram, it can be concluded that the phase is Al8Fe2Si; The point 5 contains a large amount of Al element, and the content is 98.85%, so it is known that the phase is α-Al.

![Figure 6. SEM of steel / aluminum interface after hot-dip ZL101 melt for 15min.](image)

|   | Chemical composition (at.%) |
|---|-----------------------------|
|   | Al  | Fe  | Cr  | Si  |
| 1 | 61.57 | 24.79 | 7.30 | 6.34 |
| 2 | 68.53 | 18.13 | 5.57 | 7.77 |
| 3 | 70.42 | 14.63 | 6.64 | 14.63 |
| 4 | 72.12 | 13.90 | 5.79 | 8.19 |
| 5 | 98.85 | 0.25 | 0.15 | 0.76 |

Figure 7 is the microhardness chart of the interface of the cast sample after the steel is hot-dip in molten ZL101 for 15 minutes. It can be seen from the figure that the micro hardness of the steel matrix is about 370 HV, that of the aluminum alloy is about 60 HV, and that of the diffusion layer is 528 HV at the highest.
Compared with hot-dip pure aluminum, the thickness of the diffusion layer formed by hot-dip ZL101 is smaller, which indicates that the Si element in ZL101 can inhibit the growth of the diffusion layer. During hot-dip ZL101, the Fe2Al5 phase near the steel matrix and Al8Fe2Si phase near the aluminum matrix are formed. The growth of the diffusion layer depends on the interdiffusion between Al and Fe. The Al atoms need to pass through the Al8Fe2Si and Fe2Al5 phase layers to combine with the Fe atom. However, the Si element can enhance the interaction potential between atoms, thereby reducing the activity of Al atoms in Al8Fe2Si and reducing the diffusion rate of Al atoms\textsuperscript{[16,17]}.

3.2. Effect of hot-dip Zn on steel / aluminum interface bonding properties

In order to further optimize the hot-dip process and reduce the production cost, pure zinc is used as the hot-dip melt to study the influence of hot-dip pure zinc on the interfacial properties of steel / aluminum bimetal materials is studied.

3.2.1. Analysis of microstructure of steel after hot dip galvanizing pure zinc

The surface cleaned and assisted-plated steel is placed in a pure zinc melt at 450±10°C for 10 minutes, then taken out, and the interface morphology is observed after cooling at room temperature. Figure 8 is the SEM image of the interface of the steel after hot-dip pure zinc. It can be seen that a diffusion layer of about 150 μm is formed on the steel surface after hot-dip pure zinc for 10 minutes. The composition of each point on the interface is shown in table 6 through EDS. According to the Fe-Zn phase diagram, it can be concluded that the diffusion layer is composed of Fe3Zn10, FeZn10 and FeZn13.

![Figure 8](image-url)
### Table 6. Composition analysis of each point on the interface of steel after hot-dip pure zinc.

| Point | Chemical composition (at.%) | Composition phase |
|-------|-----------------------------|------------------|
| Zn    | Fe  | Cr  | phase |
| 1     | 0.4 | 78.1| 21.5  | Fe   |
| 2     | 90.7| 7.4 | 1.9   | FeZn10 |
| 3     | 100.0| 0  | 0     | Zn   |
| 4     | 90.6| 7.9 | 1.5   | FeZn10 |
| 5     | 73.0| 14.4| 12.6  | Fe3Zn10 |
| 6     | 93.0| 7.0 | 0     | FeZn13 |
| 7     | 93.3| 6.7 | 0     | FeZn13 |
| 8     | 98.0| 2.0 | 0     | Zn   |

#### 3.2.2. Morphology and composition analysis of steel / aluminum interface after hot-dip pure zinc

Figure 9 is the SEM image of the steel / aluminum interface under different hot-dip pure zinc times. Figure (a), (b), (c) and (d) show the interface morphology formed by hot dip of steel in 450 ± 10 °C pure zinc melt for 5min, 10min, 15min and 20min, and then pouring 720 ± 10 °C aluminum alloy in 20s. It can be seen from the figure that the interface morphology of the samples after different hot-dip time treatments differs greatly. When the hot-dip time is 5 minutes, as shown in (a), the diffusion layer at the interface is divided into two phases, the thickness of the continuous phase is about 3-5 μm, and the thickness of the particle phase layer is about 130 μm; With the increase of hot dip time, the structure of the steel / aluminum interface bonding layer becomes more and more complicated. When the hot dip time is 10 minutes, as shown in Figure (b), the thickness of the continuous phase layer at the interface is basically unchanged, the thickness of the granular phase layer is increased to 160 μm; When the hot-dip time is 15 minutes, the thickness of the particle phase layer increases about 220 μm; when the hot-dip time is 20 minutes, the dispersed particle phases at the interface gather together and form a sheet-like structure, and the thickness of the phase layer is 289 μm. It can be seen that with the increase of the hot-dip time, the thickness of the continuous phase layer basically does not change, and the thickness of the granular phase layer increases greatly. Because the diffusion between aluminum and iron is more sufficient with the extension of time, so that the diffusion layer at the interface becomes thicker.
Figure 9. SEM image of the steel/aluminum interface under different hot-dip pure zinc times.

(a) 5min (b) 10min (c) 15min (d) 20min.

Figure 10 is SEM image of the steel/aluminum interface after hot-dip pure zinc melt for 15 min. The composition of intermetallic compounds with different morphology is shown in table 7. Combining with the ternary phase diagram of Fe-Zn-Al, we can know the Composition phase of each point. It can be concluded that the steel/aluminum interface consists of Fe2Al5Znx phase layer near the steel matrix and FeAl3Znx particle phase layer near the aluminum alloy matrix.

Figure 10. SEM image of the steel/aluminum interface after hot-dip pure zinc melt for 15 min.
During Hot-Dip pure zinc of steel, Fe atoms in steel matrix and Zn atoms in zinc melt diffuse each other, forming a continuous phase layers of FeZn10, FeZn13, and Fe3Zn10 at the steel / zinc interface.

When the aluminum alloy is cast at 720 ± 10 ℃, the zinc coating on the surface of the steel melts into the aluminum alloy due to the sudden rise in temperature. Due to the short solidification time of the aluminum alloy, the distance between Fe atoms and Zn atoms is relatively short, so the contents of Fe and Zn are similar to those before pouring.

### Table 7. Composition analysis of each point on the steel / aluminum interface after hot-dip pure zinc for 15 minutes.

| Point | Chemical composition (at.%) | Composition phase |
|-------|-----------------------------|-------------------|
|       | Zn  | Fe  | Al  | Si  | Cr  |               |
| 22    | 8.4 | 19.8| 63.6| 3.8 | 4.4 | Fe2Al5Znx      |
| 23    | 2.7 | 16.1| 68.6| 4.8 | 2.2 | Fe2Al5Znx      |
| 24    | 4.7 | 15.7| 70.3| 5.7 | 3.6 | FeAl3Znx       |

During Hot-Dip pure zinc of steel, Fe atoms in steel matrix and Zn atoms in zinc melt diffuse each other, forming a continuous phase layers of FeZn10, FeZn13, and Fe3Zn10 at the steel / zinc interface. When the aluminum alloy is cast at 720 ± 10 ℃, the zinc coating on the surface of the steel melts into the aluminum alloy due to the sudden rise in temperature. Due to the short solidification time of the aluminum alloy, the distance between Fe atoms and Zn atoms is relatively short, so the contents of Fe and Zn are similar to those before pouring.

### 3.2.3. Analysis of interface microhardness after hot-dip pure zinc

In order to study the mechanical properties of the steel / aluminum bimetal interface after hot-dip pure zinc, the microhardness test is performed on the bimetals formed under different hot-dip times, the results are shown in Figure 11. From left to right in the figure are the microhardness of aluminum alloy, diffusion layer (diffused phase, continuous phase), and steel matrix. It can be seen from the figure that the microhardness of the steel matrix is 226–380HV; the microhardness of the aluminum matrix is 60–100HV; the maximum microhardness of the diffusion layer is 425–640HV, which is higher than the hardness of the matrix, and the microhardness of continuous phase is higher than that of the dispersed phase. Compared with hot-dip pure aluminum, the micro hardness and toughness of bimetal interface formed by hot-dip pure zinc are improved, which reduces the brittle fracture and increases the interface adhesion. It can also be seen from the figure that the interface width increases with the increase of hot-dip time, because the diffusion among Fe, Al and Zn atoms is more sufficient with the increase of time.

![Figure 11. Microhardness distribution of steel / aluminum interface at different times of hot-dip pure zinc.](image-url)
3.2.4. Growth kinetics analysis of steel / aluminum interface diffusion layer after hot-dip pure zinc. Figure 12 shows the thickness change of the steel / aluminum composite diffusion layer under different hot-dip pure zinc plating times. According to the method described in 2.1.4, the thickness of the interfacial diffusion layer under different hot-dip times is substituted into the formula (2) for fitting, and the curve obtained is shown in the figure. From the figure, the slope of the curve is \( n = 0.56038 \); the intercept is \( \ln k = -12.20804 \). Substituting the data into the equation (2), the equation is:

\[
\ln \Delta x = 0.56038 \ln t - 12.20804 \tag{5}
\]

By finishing formula (5), the growth kinetic equation of the thickness \( \Delta x \) of the hot-dip galvanized steel / aluminum bimetal interface diffusion layer with the hot-dip plating time \( t \) is obtained:

\[
\Delta x = 4.9902 \times 10^{-6} t^{0.56038} \tag{6}
\]

![Figure 12. Relationship between \( \ln \Delta x \) and \( \ln t \).](image)

Among them, the kinetic index \( n = 0.56038 \), and the reaction rate \( k = 4.9902 \times 10^{-6} \). \( n \) is close to 0.5, which indicates that the thickness of the diffusion layer is proportional to the square root of the hot-dip time, the diffusion layer meets the parabolic growth rule. The growth of the diffusion layer is controlled by bulk diffusion, that is intra-grain diffusion, and the substitution of Fe and Zn to overcome the lattice resistance of the primary intermetallic compound phase for diffusion.

4. Conclusions

(1) The steel/aluminum bimetal prepared by hot-dip pure aluminum pretreatment of steel realizes metallurgical bonding, and an intermetallic compound phase layer mainly composed of Fe2Al5 is formed on the interface.

(2) The steel/aluminum bimetal interface prepared by hot-dip ZL101 is composed of Fe2Al5 phase near the steel matrix and Al8Fe2Si phase near the aluminum alloy.

(3) Compared with hot-dip pure aluminum, the thickness of the diffusion layer formed by hot-dip ZL101 is smaller, because the Si in the Al8Fe2Si phase formed at the interface hinders the diffusion of Al atoms.

(4) The steel / aluminum bimetal interface prepared by hot-dip pure zinc pretreatment consists of Fe2Al5Znx continuous phase layer near the steel matrix and FeAl3Znx dispersed phase layer near the aluminum alloy substrate side.
The microhardness of the steel/aluminum bimetal interface obtained by hot-dip pure aluminum, ZL101, and pure zinc are 563.5HV, 528.3HV, 632.3HV, respectively.

The growth kinetics of the steel/aluminum bimetal interface diffusion layer is studied. It can be seen that when the pure aluminum is hot-dipped, the growth kinetics of the thickness of the interface diffusion layer and the hot-dip plating time satisfy the equation: 

$$\Delta x = 5.57 \times 10^{-7}t^{0.56501}$$

The diffusion rate 

$$k = 5.57 \times 10^{-7}$$

The growth of the diffusion layer is controlled by bulk diffusion; when pure zinc is hot-dipped, the thickness of the interface diffusion layer and the hot-dip time meet the equation:

$$\Delta x = 4.9902 \times 10^{-6}t^{0.56038}$$

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