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Interfacial structure of steel-Al-28Pb bonding plate with semisolid rolling-casting method①

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Abstract: Fe-Al compound at the interface of steel-mushy Al-28Pb bonding plate was studied quantitatively. The relationship between ratio of Fe-Al compound at interface and bonding parameters such as preheating temperature of steel plate, solid volume fraction of Al-28Pb slurry and rolling speed, was established by artificial neural networks perfectly. The results show that when the bonding parameters are 546 ℃ for preheating temperature of steel plate, 43.5% for solid volume fraction of Al-28Pb slurry and 8.6 mm/s for rolling speed, the reasonable ratio of Fe-Al compound corresponding to the largest interfacial shear strength of bonding plate is obtained as 71.5%. This reasonable ratio of Fe-Al compound is a quantitative criterion of interfacial embrittlement, that is, when the ratio of Fe-Al compound at interface is larger than 71.5%, interfacial embrittlement will occur.

Key words: interfacial structure; Fe-Al compound; artificial neural networks
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1 INTRODUCTION

Steel-Al-28Pb bonding plate is an ideal material of neotype bearing[1-3], which are widely needed in machinery and automobile fields[4-6]. For this bonding plate, interfacial structure is very important. It determines the interfacial mechanical property. Fe-Al solid solution and Fe-Al compound are the component materials of interface of steel-Al-28Pb bonding plate. When interface is completely made up of Fe-Al solid solution (for example the interface formed by the bonding of solid steel to solid Al-28Pb), interfacial mechanical property is generally lower, usually only about 40 MPa[7]. When interface is entirely made up of Fe-Al compound (for example the interface formed by the bonding of solid steel to liquid Al-28Pb), the interface becomes brittle, and interfacial mechanical property is not very high, usually of about 60 MPa[8]. When interface is made up of Fe-Al compound and Fe-Al solid solution (for example the interface formed by the bonding of solid steel to mushy Al-28Pb), interfacial mechanical property can increase to about 70 MPa[9]. Therefore, it is very important to determine the interfacial structure of steel-Al-28Pb bonding plate quantitatively.

It is well known that the formation of interface is the result of diffusion of Al atoms into steel substrate and reaction with Fe atoms[10]. Therefore, the bonding parameters, which can influence the diffusion and reaction of Al atoms in bonding, have important effects on the interfacial structure of steel-Al-28Pb bonding plate.

In this work, the interfacial structure of steel-mushy Al-28Pb bonding plate was studied quantitatively. The relationship between interfacial structure and bonding parameters (such as preheating temperature of steel plate, solid fraction of Al-28Pb slurry and rolling speed) was established by artificial neural networks, and the reasonable interfacial structure was determined.

2 EXPERIMENTAL

The materials used in this experiment were 08Al steel plate with thickness of 1.2 mm and Al-28Pb (mass fraction, %) alloy which contains 1.0% Si.

The experimental procedures were as follows.

1) Treating the steel plate surface. Defatting and descaling the surface to get fresh surface. Then immersing the surface in 7% aqueous solution of flux (K_2ZrF_6) at 90 ℃. The immersing time was 1 min. These conditions could form a 10 μm-thick flux layer

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on the surface of steel plate, which prevents the fresh surface from oxidizing. At last stoving the steel plate for 1 min at 200 ℃ in order to remove the water in flux layer.

2) Preparing Al-28Pb slurry. Electromagnetic-mechanical stirring technique was used to prepare Al-28Pb slurry[11]. The precision of solid volume fraction of Al-28Pb slurry was ±1%.

3) Conducting steel-mushy Al-28Pb bonding. The experimental equipment is shown in Fig. 1. The length of pouring mouth is 200 mm. The diameter of roller is 320 mm. The precision of temperature is ±1 ℃. The precision of rolling speed is ±0.1 mm/s, and the thickness of bonding plate is 2.5 mm.

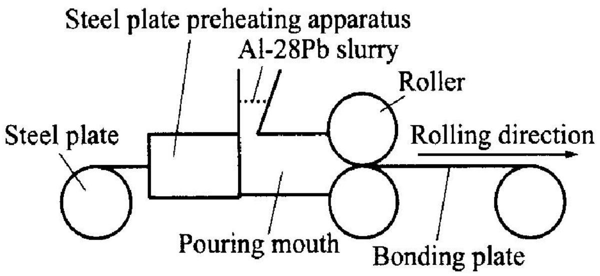

Fig. 1 Sketch of steel-mushy Al-28Pb bonding process

4) Cutting up the bonding plate into testing samples for SEM experiment using linear cutting method. The sample was a block of 10 mm × 10 mm × 2.5 mm. One side of this sample must be carefully ground, polished, eroded, cleaned and dried. The content of etching liquid was 0.5% HF, 1.5% HCl, 2.5% HNO_3 and 95.5% H_2O.

5) Conducting SEM experiment to observe the interfacial structure.

3 RESULTS AND DISCUSSION

3.1 Relationship between content of Fe-Al compound and bonding parameters

For Al-28Pb slurry, primary solid particles distribute in liquid uniformly. In process of steel-mushy Al-28Pb bonding, the primary solid particles and liquid in the uniform Al-28Pb slurry contact with steel plate in some proportion respectively. The difference of diffusion and reaction capability between liquid and solid Al atoms results in the interface which is made up of Fe-Al compound and Fe-Al solid solution alternatively[9, 12]. This interfacial structure is periodic as shown in Fig. 2. Thus one period can be used to determine the interfacial structure of steel-mushy Al-28Pb bonding quantitatively. L_1/L is named as ratio of Fe-Al compound at interface. L_1 is the length of Fe-Al compound in one period. L is the length of one period, namely, the sum of L_1 and L_2 (the length of Fe-Al solid solution in one period). The experimental data (average value) of ratio of Fe-Al compound at interface are shown in Table 1.

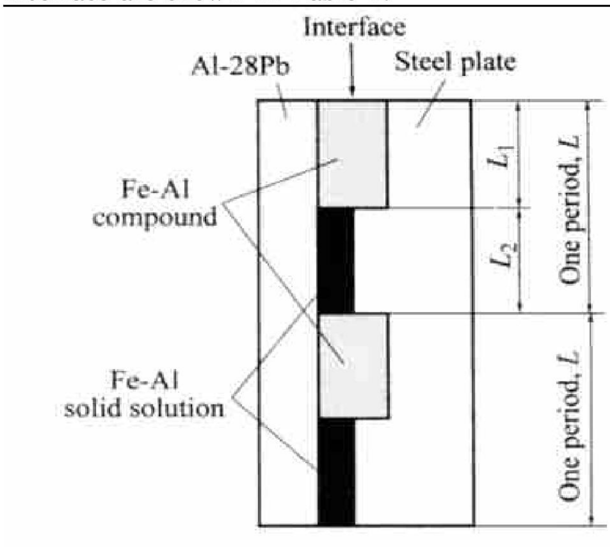

Fig. 2 Interface of steel-mushy Al-28Pb bonding plate

In steel-mushy Al-28Pb bonding, the bonding parameters such as preheating temperature of steel plate, solid volume fraction of Al-28Pb slurry and rolling speed have some influences on ratio of Fe-Al compound at interface. There exists a complicated nonlinear relationship between bonding parameters and ratio of Fe-Al compound at interface. This relationship is rather difficult to or can not to be predicted by conventional regression method.

Artificial neural networks (ANN) have been widely used to realize modeling, estimation, prediction, diagnosis and adaptive control in complex nonlinear system[13-15]. The back-propagation (BP) network is a multilayer feedforward and full-connected neural networks. It has strong associative memory and generalization capabilities, and can approximate any nonlinear continuous function with an arbitrary precision. Therefore artificial neural networks can be used to establish the model about the relationship between bonding parameters and ratio of Fe-Al compound at interface in steel-mushy Al-28Pb bonding.

A three-layered feed-forward neural networks system with 3 neurons in the input layer, 2 in the hidden layer and 1 in the output layer was used in this investigation as shown in Fig. 3. Layer Ⅰ is the input layer which uses linear elements Z_1, Z_2 and Z_3 representing preheating temperature of steel plate, solid volume fraction of Al-28Pb slurry and rolling speed, respectively. Layer Ⅱ is the hidden layer which uses nonlinear elements. The input of element J is N_j which is the sum of the outputs of layer Ⅰ after timing weight respectively, and the output of element J is Y_j which is the result of the nonlinear function of N_j named as $f(x)$. Layer Ⅲ is the output layer which uses only one nonlinear

Table 1 ANN training and predication points

Sample	Preheating temperature of steel plate/ ℃	Solid volume fraction of mushy/ %	Rolling speed / (mm·s⁻¹)	Ratio of Fe-Al compound/ %		Relative error/ %
				Test	Desired	
1	150	40	10	2.0	2.0	0.0
2	200	40	10	4.8	4.9	2.1
3	350	40	10	20.3	19.7	2.9
4	450	40	10	52.5	53.8	2.5
5	500	40	10	56.2	56.1	0.2
6	550	40	10	83.1	84.3	1.4
7	600	40	10	85.8	84.9	1.0
8	550	15	10	98.6	97.3	1.3
9	550	20	10	94.7	95.1	0.4
10	550	25	10	93.2	94.2	1.1
11	550	30	10	85.3	87.6	2.7
12	550	35	10	83.9	83.9	0.0
13	550	45	10	65.1	66.4	2.0
14	550	55	10	46.8	47.9	2.4
15	550	60	10	44.0	45.9	4.3
16	550	40	2	100	100	0.0
17	550	40	5	93.2	94.1	1.0
18	550	40	20	28.6	28.1	1.7
19*	250	40	10	5.5	5.6	1.8
20*	650	40	10	77.6	75.3	3.0
21*	550	50	10	53.1	53.4	0.6
22*	550	40	15	41.3	40.9	1.0

* —Testing sample

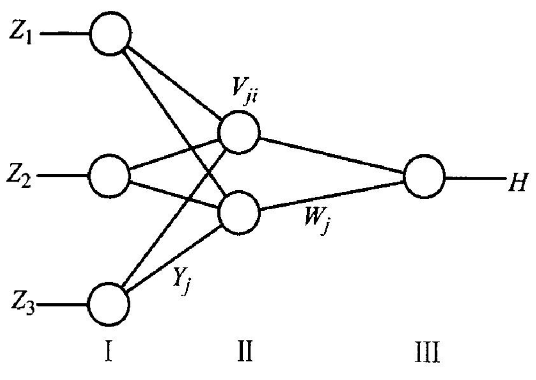

Fig. 3 Back-propagation structure of ANN

element whose input N is the sum of the outputs of layer II (Y_j) after timing weight respectively, and the output, also the output of ANN, is the ratio of Fe-Al compound at interface (H) which is the result of the nonlinear function of N named as $f(x)$. V_{ji} is the connection weight between the input layer and the hidden layer. W_j is the weight between the hidden layer and the output layer.

The learning algorithm could be summarized as follows.

1) Selecting the learning rate $\eta = 0.1$, momentum coefficient $\alpha = 0.1$ and $Z_4 = Y_3 = -1$.

2) Taking a group of random numbers within $(-0.5, 0.5)$ as the initial values of V_{ji} and W_j.

3) Computing the outputs of all neurons layer by layer, starting with the input layer as

$$net_j = \sum_{i=1}^{4} V_{ji} Z_i \qquad j = 1, 2 \tag{1}$$

$$Y_j = f(net_j) \tag{2}$$

$$net = \sum_{j=1}^{3} W_j Y_j \tag{3}$$

$$H = f(net) \tag{4}$$

$$f(x) = (1 - e^{-x})/(1 + e^{x}) \tag{5}$$

V_{j4} and W_3 offer thresholds for the neurons in the hidden layer and output layer because the output value of Z_4 and Y_3 are constant and equals to -1.

4) Computing system error

$$E = \frac{1}{2P} \sum_{n=1}^{P} (D_n - H_n)^2 \tag{6}$$

where P represents the total number of patterns,

H_n is the ANN outputs and D_n the desired outputs.

5) If E is small enough or learning iteration is big enough, stop learning.

6) Computing learning errors for all neurons layer by layer:

$$\delta_H = (D - H) f'(net) \tag{7}$$

$$\delta_j = W_j \delta_H f'(net_j), \quad j = 1, 2 \tag{8}$$

7) Updating weights along negative gradient of E:

$$W_j(t+1) = W_j(t) + \eta \delta_H Y_j + a[W_j(t) - W_j(t-1)] \tag{9}$$

$$V_{ji}(t+1) = V_{ji}(t) + \eta \delta_j Z_i + a[V_{ji}(t) - V_{ji}(t-1)] \tag{10}$$

8) Repeating by going to Step 3).

Randomly selecting 18 samples to train the ANN and the remaining 4 samples to verify the generalization capability of the ANN. After 62 000 iterations, the outputs H of the ANN are close enough to the desired outputs D, not only for training samples but also for testing samples. The results are shown in Table 1. The maximum of relative error is 4.3%. This fact shows that the ANN is good enough.

3.2 Determination of reasonable ratio of Fe-Al compound at interface

The reasonable ratio of Fe-Al compound at interface is corresponding to the largest interfacial mechanical property. In the study on mechanical property of steel-mushy Al-28Pb bonding, the bonding parameters for the largest interfacial shear strength were obtained. They are 546 ℃ for preheating temperature of steel plate, 43.5% for solid volume fraction of Al-28Pb slurry and 8.6 mm/s for rolling speed. From these bonding parameters, the reasonable ratio of Fe-Al compound at interface is 71.5% using the relationship established by the artificial neural networks.

3.3 Discussion

For steel-mushy Al-28Pb bonding, under the conditions of low preheating temperature of steel plate, large solid volume fraction of Al-28Pb slurry and high rolling speed, the diffusion and reaction of Al atoms were limited. Fe-Al solid solution formed at the interface, but only very little Fe-Al compound can be formed, so the ratio of Fe-Al compound at interface is rather small. With increasing preheating temperature of steel plate and decreasing solid volume fraction of Al-28Pb slurry and rolling speed, the diffusion and reaction of Al atoms increase gradually. More and more Fe-Al compounds form at the interface, and thus the ratio of Fe-Al compound at interface becomes larger and larger.

At the interface, Fe-Al solid volume solution formed weaker bonding, and Fe-Al compound formed stronger metallurgic bonding. When ratio of Fe-Al compound at interface was smaller, too more Fe-Al solid solution at the interface could result in the lower interfacial mechanical property directly. So this interfacial structure with too little Fe-Al compound was not good. However, when ratio of Fe-Al compound at interface was too larger, too more Fe-Al compound could result in interfacial embrittlement, and the interfacial mechanical property also was lowered. When the ratio of Fe-Al compound at interface was 71.5%, Fe-Al compound at interface not only kept the strong metallurgic bonding, but also avoided the interfacial embrittlement. Thus the interfacial mechanical property was the largest and this interfacial structure was very reasonable. Therefore, 71.5% was a quantitative criterion of interfacial embrittlement, namely, when ratio of Fe-Al compound was larger than 71.5%, interfacial embrittlement would occur and the interfacial mechanical property decreased. Fig. 4 is the typical reasonable interface of steel-mushy Al-28Pb bonding. The right side is Al-28Pb region. The left side is 08Al steel plate. Regions 1 and 3 are Fe-Al compounds. Region 2 is Fe-Al solid solution.

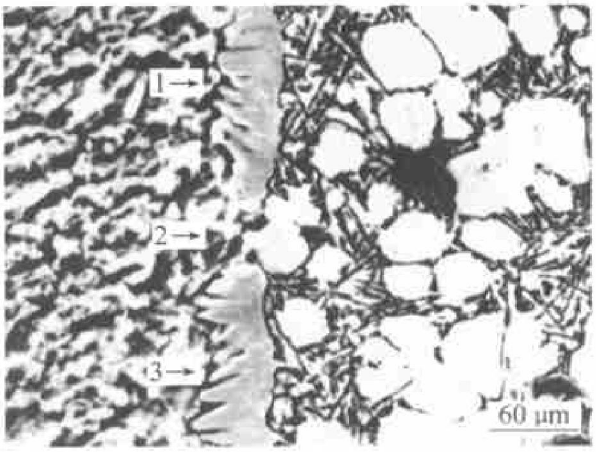

Fig. 4 Reasonable interfacial morphology of bonding plate

4 CONCLUSIONS

1) The relationship between ratio of Fe-Al compound at interface and bonding parameters such as preheating temperature of steel plate, solid volume fraction of Al-28Pb slurry and rolling speed in steel-mushy Al-28Pb bonding can be established by artificial neural networks perfectly.

2) When bonding parameters are 546 ℃ for preheating temperature of steel plate, 43.5% for solid volume fraction of Al-28Pb slurry and 8.6 mm/s for rolling speed, the reasonable ratio of Fe-Al compound at interface of 71.5%, corresponding to the highest interfacial mechanical property, can be got.

3) The ratio of Fe-Al compound at interface should not be larger than 71.5%. This value is a quantitative criterion of interfacial embrittlement. When ratio of Fe-Al compound is larger than 71.5%,

interfacial embrittlement will occur.

REFERENCES

[1] Kenneth B. Metal Base Composite Material [M]. Beijing: National Defense Industry Press, 1982. 45 - 68.

[2] Davis J R. Aluminum and Aluminum Alloys [M]. OH: ASM International Publications, 1993. 156 - 162.

[3] ZHANG Peng, DU Yun-hui. Relationship between solid fraction and distribution of Pb in Al-Pb ingot[J]. Trans Nonferrous Metal Soc, 2001, 11(3): 409 - 412.

[4] SUN Da-ren, ZHANG Ming-zhe. Fabrication and microstructure of casting Al-Pb sliding bearing alloy[J]. Journal of Special Casting and Nonferrous Metal, 1998 (5): 24 - 26. (in Chinese)

[5] Pathak J P, Malhotra S L. Production of high-lead aluminum by impeller mixing[J]. Met Tech, 1979(11): 442 - 448.

[6] Mohan S, Ray S. The effect of lead content on wear characteristic of Astir-cast Al-Pb alloy[J]. Wear, 1990, 140: 83 - 92.

[7] LUO Zhong-an. The Study on Rolling Forming of Steel-backed Al-Pb Alloy Bearing[D]. Shenyang: Northeastern University, 1993. 26. (in Chinese)

[8] Lepper K, Chashechkina J. Sliding behavior of selected aluminum [J]. Wear, 1997, 203: 46 - 56.

[9] ZHANG Peng, DU Yun-hui. Modeling and optimizing of steel and mushy Al-28Pb alloy bonding[J]. Trans Nonferrous Metal Soc, 2001, 11(2): 239 - 243.

[10] ZHANG Peng, DU Yun-hui. Interface of solid steel and liquid aluminum under nonequilibrium diffusion [J]. Trans Nonferrous Metal Soc, 2000, 10(3): 389 - 392.

[11] ZHANG Peng, DU Yun-hui. Relationship between solid fraction of slurry and property of steel/mushy Al-20Sn semi-solid bonding[J]. Trans Nonferrous Metal Soc, 2002, 12(5): 914 - 917.

[12] FANG Jun-xin. Solid Physics [M]. Shanghai: Shanghai Science and Technology Press, 1980. 170. (in Chinese)

[13] Hopfield D A. Diagonal recurrent neural networks for dynamics control [J]. J Proc Nat Acad Sci USA, 1982, 79: 2554 - 2559.

[14] Psaltis D, Sideris A. Tamanmuya P. Multilayered neural network controller [J]. IEEE Control Syst Mag, 1988(8): 17 - 23.

[15] Song R, Zhang Q. The application of artificial neural networks to the investigation of aging dynamics in 7175 aluminium alloys[J]. Mat Sci Eng, 1995, C3: 39 - 43.

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