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Modeling and optimizing of steel and mushy Al-28Pb alloy bonding①

ZHANG Peng(张 鹏)[1], DU Yun-hui(杜云慧)[1], ZENG Da-ben(曾大本)[1],
REN Xue-ping(任学平)[2], CUI Jian-zhong(崔建忠)[3], BA Li-min(巴立民)[4]
(1. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, P. R. China;
2. Department of Metal Forming, University of Science and Technology Beijing, Beijing 100083, P. R. China;
3. Department of Metal Forming, Northeastern University, Shenyang 110006, P. R. China;
4. Ansha Automobile Fittings Factory, Anshan 114014, P. R. China)

[Abstract] The bonding of steel and mushy Al-28Pb alloy was studied. The relationship model about preheat temperature of steel plate, solid fraction of mushy Al-28Pb alloy, rolling speed and interfacial shear strength of the bonding plate was established by artificial neural network perfectly. This model can be optimized by a genetic algorithm, and the optimum bonding parameters for the largest interfacial shear strength are: 546 ℃ for preheat temperature of steel plate, 43.5% for solid fraction of mushy Al-28Pb alloy and 8.6 mm/s for rolling speed, and the corresponding largest interfacial shear strength of bonding plate is 70.3 MPa.

[Key words] bonding of steel and mushy Al-28Pb alloy; artificial neural network; genetic algorithm
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1 INTRODUCTION

At present, the typical material of neotype bearing is steel-backed Al-20Sn alloy bonding plate[1]. For steel-backed Al-20Sn alloy bonding plate, steel back has high strength which can bear the external load, and Al-20Sn alloy layer is a lubricating one in which Al substrate has excellent heat conductivity and Sn particle has perfect lubricating property, so this bonding plate is very ideal for bearing. However, Sn is rather expensive, the cost of steel-backed Al-20Sn alloy bonding plate is very high (about RMB 30 000 Yuan/t), therefore, other materials have been tested to substitute for Sn in recent years. Nowadays, among the substitutes Pb is rather practicable, its cost is only one fifth as much as that of Sn, and its lubricating property can match that of Sn. So the study of Al-Pb alloy bonding plate becomes the research focus of bearing bonding plate gradually[2, 3].

Generally, the method of processing steel-backed Al-Pb alloy bonding plate falls into two classes. One is solid to solid bonding, that is, solid steel plate to solid Al-Pb alloy plate bonding[4]. The other is solid to liquid bonding, that is, solid steel plate to liquid Al-Pb alloy bonding[2]. For solid to solid bonding, the bonding form of interface is mechanically occluded together with only a little physical bonding; therefore the interfacial mechanical property is generally bad, usually only about 40 MPa, this limits the applied range of bonding plate greatly. For solid to liquid bonding, the bonding form of interface is metallurgical bonding which is the firmest one; however, the higher bonding temperature often results in Fe-Al compound (Fe_2Al_5 and $FeAl_3$) layer at interface, this embrittles the interface to a certain extent, so the interfacial mechanical property does not reach its own level, usually is about 60 MPa. Therefore, new method of processing steel-backed Al-Pb alloy bonding plate should be developed in order to increase the interfacial mechanical property of bonding plate.

In this work steel and mushy Al-28Pb alloy bonding is conducted, a relationship model about the bonding parameters and the interfacial shear strength of bonding plate is made by using artificial neural network (ANN) according to the experimental data, and the optimum technology is also optimized by a genetic algorithm successfully.

2 EXPERIMENTAL

The materials used in this work were 1.2 mm thick 08Al steel plate and Al-28Pb (%, mass fraction) alloy. The surface of 08Al steel plate was defatted, descaled and immersed. The immersing technology of steel plate was[5]: immersed in 80 ℃ flux (No.1 flux being patented) aqueous solution for 1 min, after being got out, stoved at 200 ℃ for 2 min to remove the water in flux layer on steel plate surface. Mushy Al-28Pb alloy was prepared by using electromagnetic mechanical stirring method[6].

The steel and mushy Al-28Pb alloy bonding experiment was carried on the bonding equipment

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shown in Fig. 1. The length of pour mouth was 200 mm. The diameter of roller was 320 mm. The precision of temperature was ±1 ℃. The precision of solid fraction was ±0.1%. The precision of speed was ±0.1 mm/s. The thickness of the bonding plate was 2.5 mm. The samples for interfacial shear strength were sheared on universal material testing machine. The microstructure of bonding interface was determined by SEM.

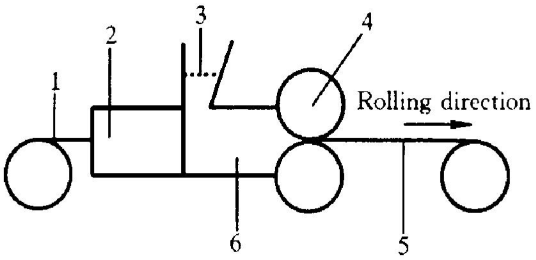

Fig. 1 Scheme of steel and mushy Al-28Pb alloy bonding

1 —Steel plate; 2 —Steel plate preheating apparatus; 3 —Mushy Al-28Pb; 4 —Roller; 5 —Bonding plate; 6 —Pour mouth

3 RESULTS AND DISCUSSION

3.1 Relationship model about bonding parameters and interfacial shear strength

The experimental data of interfacial shear strength are shown in Table 1. In steel and mushy Al-28Pb alloy bonding, bonding parameters such as preheating temperature of steel plate, solid fraction of mushy Al-28Pb alloy and rolling speed have some influences on interfacial shear strength. There exists complicated nonlinear relationship between preheating temperature of steel plate, solid fraction of mushy Al-28Pb alloy, rolling speed and interfacial shear strength. This relationship model is rather difficult or could not be determined by conventional regression method.

Artificial neural network has been widely used to realize modeling, estimation, prediction, diagnosis and adaptive control in complex nonlinear system[7~9]. The back-propagation (BP) network is a multilayer feed-forward and full-connected neural network, it has strong associative memory and generalization capabilities, and it can approximate any nonlinear continuous function with an arbitrary precision. Therefore we can use artificial neural network to establish the relationship model about bonding parameters and interfacial shear strength in steel and mushy Al-28Pb alloy bonding.

A three layered feed-forward neural network system with three neurons in the input layer, two in the hidden layer and one in the output layer was used (as shown in Fig. 2). Layer Ⅰ is input layer which uses linear elements Z_1, Z_2 and Z_3 which represent preheating temperature of steel plate, solid fraction of mushy Al-28Pb alloy and rolling speed respectively. Layer Ⅱ is 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 output layer which uses only one nonlinear 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 interfacial shear strength (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.

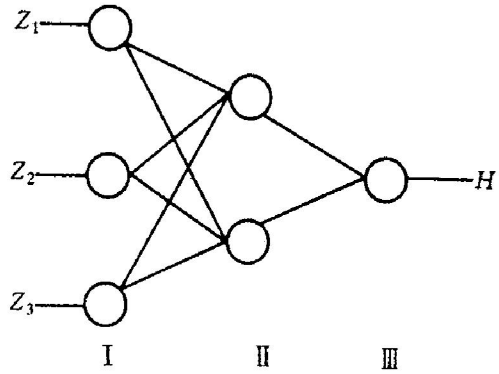

Fig. 2 Back-propagation structure of artificial neural network

The learning algorithm can be summarized as follows:

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

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

Step 3 Compute the outputs of all neurons layer by layer, starting with the input layer:

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

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

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

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

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

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

Step 4 Compute system error.

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

where P is the total number of patterns, H_n is the ANN outputs and D_n is the desired output.

Table 1 ANN training and prediction points

Sample	Preheating temperature of steel plate/ ℃	Solid fraction of mushy Al-28Pb/ %	Rolling speed /(mm·s^{-1})	Interfacial shear strength/ MPa		Relative error / %
				Tested	Desired	
1	150	40	10	7.4	7.2	2.7
2	200	40	10	12.4	12.6	1.6
3	350	40	10	36.1	36.3	0.6
4	450	40	10	60.9	60.1	1.3
5	500	40	10	67.2	67.1	0.1
6	550	40	10	68.5	69.1	0.9
7	600	40	10	67.6	68.8	1.8
8	550	15	10	60.2	61.1	1.5
9	550	20	10	63.0	63.7	1.1
10	550	25	10	64.2	66.5	3.6
11	550	30	10	67.6	66.8	1.2
12	550	35	10	68.2	67.1	1.6
13	550	45	10	69.6	68.3	1.9
14	550	55	10	62.1	62.7	1.0
15	550	60	10	60.4	62.8	3.9
16	550	40	2	58.9	61.1	3.7
17	550	40	5	64.4	63.9	0.8
18	550	40	20	45.2	46.9	3.8
19*	250	40	10	13.4	13.9	3.7
20*	650	40	10	67.3	67.4	0.1
21*	550	50	10	65.7	66.1	0.6
22*	550	40	15	57.8	57.2	1.0

* Testing sample

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

Step 6 Compute learning errors for all neurons layer by layer:

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

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

Step 7 Update weights along negative gradient of E:

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

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

Step 8 Repeat by going to Step 3.

Randomly select 18 samples to train the ANN and 4 samples remain to verify the generalization capability of the ANN. After 58000 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 3.9%. This fact shows that the ANN is good enough.

3.2 Optimum bonding technology

After modeling the relationship between H and (Z_1, Z_2, Z_3) by using ANN, a nonlinear function containing three variables, $H = (Z_1, Z_2, Z_3)$, can be obtained. The aim of this paper is to find a proper group (Z_1, Z_2, Z_3) to maximize H. This is a nonlinear optimization problem. The conventional gradient methods generally encounter one difficulty, i.e., they often result in a local maximum.

A genetic algorithm can overcome the difficulty that conventional gradient methods being encountered since it is a kind of optimization algorithm based on the law of evolution of living things, i.e., survival of the fittest, natural selection, inheritance and variation. Considering a nonlinear optimization problem in n dimensions:

$$C = f(x_1, x_2, \cdots, x_n) \tag{11}$$

randomly select m points within n dimensions to construct the population, C is used to evaluate every individual, superior and inferior. The genetic algorithm is summarized as follows:

1) Compute C_i ($i = 1, 2, \cdots, m$) for every point. Half of the population would survive. The surviving probability is proportional to the corresponding value of C_i for the ith individual.

2) Crossbreed. Copy the $m/2$ surviving individuals firstly and pair them randomly. Then exchange part elements of every pair randomly to generate new individuals.

3) Mutation. Select several individuals randomly in the population, and mutate some elements in the selected individuals (add a small random number).

4) A new generation has been generated. Return to 1) and start to breed next generation. In this way

the whole population would move to the area which corresponded to high C values. At last, some individuals are close enough to the maximum of f.

For our example, $m = 22$, $n = 3$. After the genetic algorithm worked over 3 500 iterations, the optimization point was (546, 43.5%, 8.6). Therefore, for steel and mushy Al-28Pb alloy bonding, the optimum parameters are 546 ℃ for preheating temperature of steel plate, 43.5% for solid fraction of mushy Al-28Pb alloy, 8.6 mm/s for rolling speed, and the corresponding H, namely, the maximum interfacial shear strength of bonding plate is 70.3 MPa. This optimum technology has been verified through further experiments. The experimental data are shown in Table 2.

Table 2 Optimum experimental data

Sample	Preheating temperature of steel plate/ ℃	Solid fraction of mushy Al-Pb/ %	Rolling speed /(mm·s^{-1})	Interfacial shear strength /MPa
1	546	43.5	8.6	70.2
2	546	43.5	8.6	70.3
3	546	43.5	8.6	70.3

3.3 Interface of bonding plate

Fig. 3 is the SEM micrograph of interface of the bonding plate which was prepared according to the optimum steel and mushy Al-28Pb alloy bonding technology. The left side is 08Al steel substrate. The right side is Al-28Pb alloy layer. In Al-28Pb alloy layer, the white round parts are the primary solid particles and the dark round parts are Pb particles; it can be seen that not only the primary solid particles but also Pb particles distribute rather evenly in Al-28Pb alloy layer. The juncture of steel substrate and Al-28Pb alloy layer is the interface, it can be seen that the interface of steel and mushy Al-28Pb alloy bonding plate is made up of the regions such as 1, 2 and 3. Regions 1 and 3 are made up of right layer and left teeth. The result of the multiple-point composition analysis shows that the right layer is $FeAl_3$

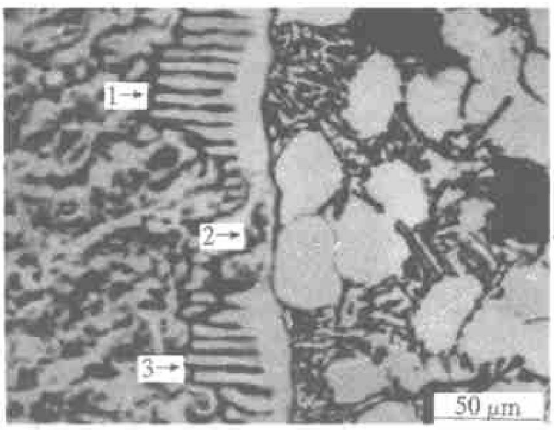

Fig. 3 SEM micrograph of interface of bonding plate

and the left tooth is Fe_2Al_5. It can be said that regions 1 and 3 are made up of Fe-Al compound $FeAl_3$ and Fe_2Al_5. The result of the multiple-point composition analysis to region 2 is Fe-Al solid solution whose aluminum content is less than 3.8%. Therefore the interface of steel and mushy Al-28Pb alloy bonding plate is made up of Fe-Al compound and Fe-Al solid solution alternatively. There is no continuous Fe-Al brittle compound layer at the interface.

3.4 Discussion

It is well known that the formation of Fe-Al compound is the result of diffusion of aluminum atoms in the inner of steel substrate and reaction with Fe atoms[10]. For steel and mushy Al-28Pb alloy bonding, when mushy Al-28Pb alloy contacts with the surface of steel plate, the primary solid particles and liquid Al-28Pb alloy contact with steel substrate in some proportion respectively. The liquid aluminum atom has higher energy, its diffusion and reaction ability is larger[11], so there exist severe diffusion and reaction at the place where liquid Al-28Pb alloy contacts with steel substrate; here occurs the Fe-Al compound, and the interfacial structure here is the same as that of steel-aluminum solid to liquid bonding. However, the solid aluminum atom has lower energy, its diffusion and reaction ability is smaller. Furthermore, the contact of primary solid particles with solid steel plate is not as close as that of liquid Al-28Pb alloy with solid steel plate. So there exists little diffusion at the place where primary solid particles contact with steel substrate, here only occurs the Fe-Al solid solution. Thus the interface of steel and mushy Al-28Pb alloy bonding plate is made up of Fe-Al compound and Fe-Al solid solution alternatively.

To steel and mushy Al-28Pb alloy bonding plate, Fe-Al solid solution forms weaker bonding, and Fe-Al compound forms much stronger metallurgical bonding. When the bonding parameters limit the diffusion and reaction of aluminum, the weaker bonding, i.e., Fe-Al solid solution would form at the interface. So under the condition of too low preheating temperature of steel plate, too large solid fraction of mushy Al-28Pb alloy and too high rolling speed, the interfacial shear strength is rather lower. When the bonding parameters admit sufficient diffusion and reaction of aluminum, the stronger metallurgical bonding, i.e., Fe-Al compound would form at the whole interface. However, when Fe-Al compound forms an entire layer, the interfacial embrittlement would happen. So under the condition of too high preheating temperature of steel plate, too little solid fraction of mushy Al-28Pb alloy and too small rolling speed, the interfacial shear strength is also lower. Only when the bonding parameters admit moderate diffusion and reaction of aluminum, for example, when the bonding parameters are 546 ℃ for preheating temperature of steel plate, 43.5% for solid fraction of mushy Al-28Pb alloy, 8.6mm/s for rolling speed, the interface of bonding plate can be made up of Fe-Al compound and Fe-Al solid solution in moderate proportion (as shown in Fig. 3). In this structure, the Fe-Al solid solution destroys the layer structure of Fe-Al compound and avoids the embrittlement of the entire interface of bonding plate, so the interfacial shear strength is the largest.

4 CONCLUSIONS

1) Steel and mushy Al-28Pb alloy bonding is a new good technology for processing steel-Al-28Pb alloy bonding plate.

2) Artificial neural network can establish the relationship model about the bonding parameters and the interfacial shear strength of bonding plate in steel and mushy Al-28Pb alloy bonding perfectly.

3) A genetic algorithm can optimize the model established by artificial neural network successfully. The optimum technology is 546 ℃ for preheating temperature of steel plate, 43.5% for solid fraction of mushy Al-28Pb alloy, 8.6 mm/s for rolling speed, and the maximum interfacial shear strength of bonding plate is 70.3 MPa.

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