Article ID: 1003-6326(2003)04-0785-05

Mechanical relationship in steel-aluminum solid to liquid bonding①

ZHANG Peng(张 鹏)[1], DU Yun-hui(杜云慧)[1], LIU Han-wu(刘汉武)[1],
ZENG Da-ben(曾大本)[2], CUI Jian-zhong(崔建忠)[3], BA Li-min(巴立民)[4]

(1. Department of Mechanical Engineering, Northern Jiaotong University, Beijing 100044, China;
2. Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China;
3. Metal Forming Department, Northeastern University, Shenyang 110006, China;
4. Anshan Automobile Fittings Factory, Anshan 114014, China)

Abstract: The bonding of solid steel plate to liquid aluminum was studied by using rapid solidification. The relationship between the bonding parameters such as preheat temperature of steel plate, temperature of aluminum liquid and bonding time, and the interfacial shear strength of bonding plate was established by artificial neural networks perfectly. This relationship was optimized with a genetic algorithm. The optimum bonding parameters are: 226 ℃ for preheat temperature of steel plate, 723 ℃ for temperature of aluminum liquid and 15.8 s for bonding time, and the largest interfacial shear strength of bonding plate is 71.6 MPa.

Key words: bonding; steel plate; liquid aluminum; rapid solidification; artificial neural networks; genetic algorithm

CLC number: TD 146 **Document code:** A

1 INTRODUCTION

The current products of solid steel plate to liquid aluminum include hot-dip aluminizing steel plate[1, 2] and steel-aluminum solid to liquid bonding plate mainly[3, 4]. They are widely used in ornament, machinery, automobile and navigation field. For these products, the interfacial mechanical property is crucial; it determines the quality and application of these products. The larger the interfacial mechanical property, the wider the application of the product.

The interfacial mechanical property is determined by interfacial structure. The matters, which can consist of interface, include Fe-Al solid solution and Fe-Al compound[5]. Fe-Al solid solution forms weak combination. Fe-Al compound forms strong combination. But when Fe-Al compound forms a thick continuous layer, interfacial embrittlement will happen. The larger the thickness of the layer, the grievous the interfacial embrittlement, and the lower the interfacial mechanical property.

It is well known that the formation of the interface is the result of diffusion of Al atoms to steel substrate and reaction with Fe atoms[6]. Therefore, the conditions, which can influence the diffusion of Al atoms, will have a crucial influence on the interfacial mechanical property.

In this paper, the bonding of solid steel plate to liquid aluminum is conducted using rapid solidification. A relationship between bonding parameters (such as preheat temperature of steel plate, temperature of aluminum liquid and bonding time) and interfacial shear strength is made using artificial neural networks. Furthermore, this relationship is optimized with a genetic algorithm successfully.

2 EXPERIMENTAL

The materials used in this experiment were 1.2 mm-thick 08Al steel plate and industry pure aluminum (99.99%).

The experimental procedures were as follows.

1) The 08Al steel plate was welded to the bottom of cooling box for rapid solidification. Fig. 1 shows the sketch of cooling box.

2) The steel plate surface was treated. Firstly the surface was defatted and descaled to get fresh surface. Secondly the surface was immersed in flux (K_2ZrF_6) aqueous solution. The concentration of the solution was 7%. The temperature of the solution was 90 ℃. The immersing time was 1 min. These conditions could form a 10 μm-thick flux layer on the steel plate surface. The action of this flux layer was to prevent the fresh surface from oxidizing. Thirdly

① **Foundation item:** Project (50274047) supported by the National Natural Science Foundation of China and Project (715-009-060) supported by the Advanced Technical Committee of China

Received date: 2002-07-09; **Accepted date:** 2002-09-28

Correspondence: ZHANG Peng, Professor, PhD; Tel: +86-10-51682226; E-mail: zhangp9@263.net

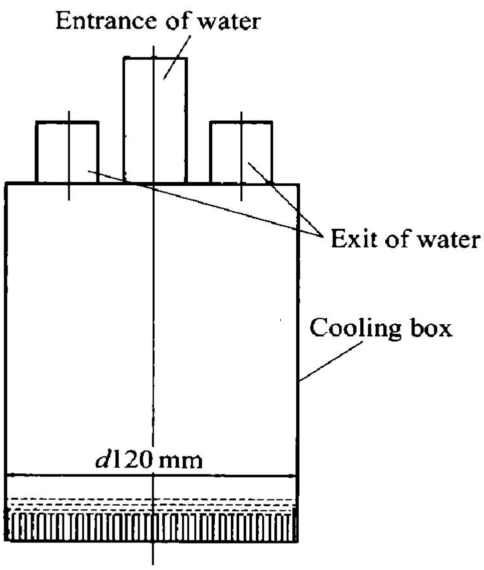

Fig. 1 Sketch of cooling box

the steel plate was stoved for 1 min at 200 ℃ in order to remove the water in the flux layer.

3) Solid to liquid bonding was conducted. Firstly the cooling box was placed onto the supporting frame. The experimental apparatus is shown in Fig. 2. Secondly the cooling box was preheated and dropped into the aluminum liquid to realize the diffusion of Al atoms to the inner of steel substrate. After a certain time, the cooling water was pumped into the cooling box immediately to realize the rapid solidification (the cooling speed was about 2 000 ℃/s), and the cooling box was raised at a speed of 10 m/s (a 4 mm-thick solid aluminum layer was obtained on steel plate) at the same time. The aluminum liquid was refined. In order to prevent the aluminum liquid from being oxidized, the liquid surface must be covered by a layer of preservative.

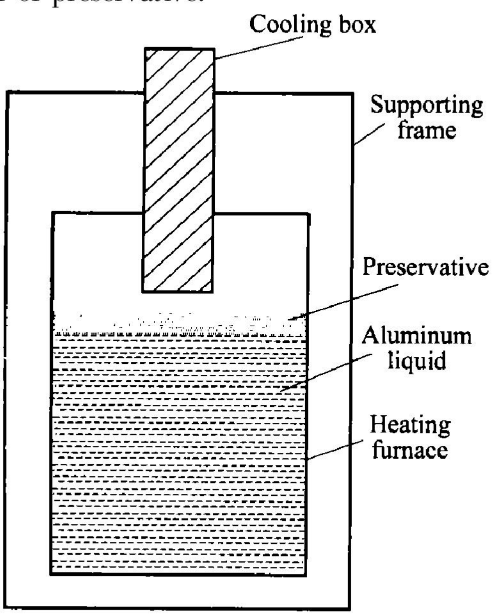

Fig. 2 Sketch of experimental apparatus

4) The cooling box was removed from the supporting frame and the bonding plate was cut from the cooling box on a lathe.

5) The interfacial shear strength was measured on universal material testing machine. The testing samples (shown in Fig. 3) were made from the bonding plate using linear cutting method.

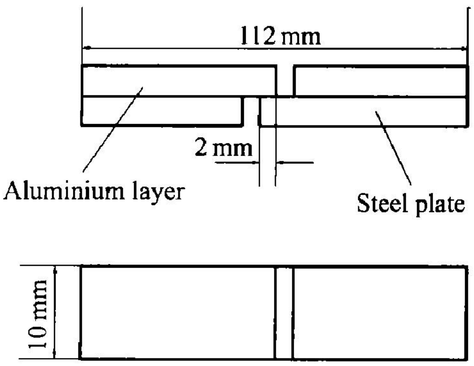

Fig. 3 Testing sample for interfacial shear strength

3 RESULTS AND DISCUSSION

3.1 Relationship between bonding parameters and interfacial shear strength

The experimental data are shown in Table 1. In steel-aluminum solid to liquid bonding, the bonding parameters such as preheat temperature of steel plate, temperature of aluminum liquid and bonding time have some influences on interfacial shear strength of bonding plate. There exists complicated nonlinear relationship between these bonding parameters and interfacial shear strength. This relationship is rather difficult to determine by conventional regression method.

Artificial neural networks (ANN) has been widely used to realize modeling, estimation, prediction, diagnosis and adaptive control in complex nonlinear system[7-11]. The back-propagation (BP) network is a multilayer feed forward and full-connected neural networks. It has strong associative memory and generalization capabilities, and it can approximate any nonlinear continuous function with an arbitrary precision. Therefore artificial neural networks can be used to establish the relationship between the bonding parameters and interfacial shear strength in steel-aluminum solid to liquid bonding.

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 is used in this paper (as shown in Fig. 4). Layer Ⅰ is input layer which uses linear elements Z_1, Z_2 and Z_3 for representing preheat temperature of steel plate, temperature of aluminum liquid and bonding time respectively. Layer Ⅱ is hidden layer which uses nonlinear elements. The input of element j is N_j which is the sum

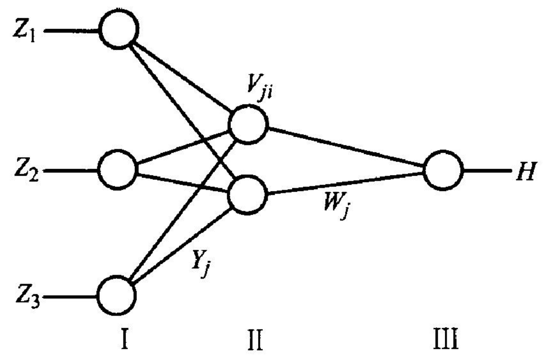

Fig. 4 Back-propagation structure of artificial neural networks

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.

The learning algorithm can be summarized below.

1) The learning rate $\eta = 0.1$, momentum coefficient $\alpha = 0.1$ and $Z_4 = Y_3 = -1$ are selected.

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

3) Starting with the input layer as follows, the outputs of all neurons are computed layer by layer.

Table 1 ANN training and predication points

Sample No.	Preheat temperature of steel plate / ℃	Temperature of aluminum liquid / ℃	Bonding time / s	Interfacial shear strength/ MPa		Relative error / %
				Tested	Desired	
1	100	670	10	4.3	4.4	2.3
2	150	670	10	18.9	19.3	2.1
3	250	670	10	58.6	56.4	3.8
4	300	670	10	65.3	65.2	0.2
5	350	670	10	69.5	68.3	1.7
6	250	700	6	50.9	52.1	2.4
7	250	700	14	70.6	70.5	0.1
8	250	700	26	60.1	62.7	4.3
9	250	700	30	54.6	54.6	0.0
10	250	700	35	53.4	53.3	0.2
11	200	750	6	53.7	54.6	1.7
12	200	750	14	71.1	71.4	0.4
13	200	750	20	68.2	68.9	1.0
14	200	750	30	52.6	50.8	3.4
15	200	750	35	52.1	52.1	0.0
16	250	720	10	68.9	67.2	2.5
17	250	740	10	67.1	67.3	0.3
18	250	760	10	60.2	59.2	1.7
19	250	780	10	54.6	55.1	0.9
20*	200	670	10	36.5	36.8	0.8
21*	250	700	20	69.3	68.1	1.7
22*	200	750	26	59.3	59.3	0.0
23*	250	680	10	62.1	60.4	2.7

* —Testing sample

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

$$Y_j = f(\mathrm{net}_j) \tag{2}$$

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

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

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

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

4) The system error is computed by

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

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

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

6) The learning errors for all neurons are computed layer by layer

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

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

7) The weights are updated 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) The learning is repeated by going to 3).

Nineteen samples are selected randomly to train the ANN, and the four remained samples are selected to verify the generalization capability of the ANN. After 75 000 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 relative error is 4.3%. It can be said that the ANN is good enough.

3.2 Optimization of relationship

After modeling the relationship between H and (Z_1, Z_2, Z_3) by using ANN, a nonlinear function containing 3 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. But a genetic algorithm can overcome the difficulty that gradient methods encounters since it is a kind of optimization algorithm based on the law of evolution of living things, such as survival of the fittest, natural selection, inheritance and variation. Considering a nonlinear optimization problem in n dimensions:

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

m points are selected randomly 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) C_i($i = 1, 2, \ldots, m$) is computed for every point. Half of the population will survive. The surviving probability is proportional to the corresponding value of C_i for the ith individual.

2) The $m/2$ surviving individuals are copied firstly and paired randomly. Then a part of elements of every pair are exchanged randomly to generate new individuals.

3) Several individuals in the population are selected randomly, and some elements in the selected individuals are mutated (a small random number is added).

4) A new generation has been generated. Return to 1) and start to breed next generation. In this way the whole population will move to the area which corresponds to high C values. At last, some individual is close enough to the maximum of f.

For our example, $m = 23$, $n = 3$. After the genetic algorithm worked over 2 800 iterations, the optimization point was 226, 723 and 15.8. Therefore, for steel-aluminum solid to liquid bonding, the optimum bonding parameters are 226 ℃ for preheat temperature of steel plate, 723 ℃ for temperature of aluminum liquid, 15.8 s for bonding time, and the corresponding H, namely, the maximum interfacial shear strength of bonding plate is 71.6 MPa. These optimum conditions have been verified through further experiments. The experimental data are shown in Table 2.

Table 2 Optimum experimental data

Sample No.	Preheat temperature of steel plate / ℃	Temperature of aluminum liquid / ℃	Bonding time / s	Interfacial shear strength/ MPa
1	226	723	15.8	71.5
2	226	723	15.8	71.6
3	226	723	15.8	71.7
4	226	723	15.8	71.5

3.3 Discussion

For steel-aluminum solid to liquid bonding, when aluminum liquid is contacted with the steel plate surface, the bonding behaviors such as wetting, spreading, adsorption, diffusion and reaction would happen[12]. In this experiment, the bonding behaviors can be accelerated under the action of the flux layer on the steel plate surface. However, it will need some time for this layer to melt and decompose, and thus the diffusion of Al atoms to the inner of steel plate decelerates. When the bonding parameters limit the diffusion of Al atoms, only Fe-Al solid solution can form weak combination at the interface. Therefore, under the condition of too low preheat temperature of steel plate, too low temperature of aluminum liquid and too short bonding time, the interfacial shear strength is rather small. Nevertheless, when the bonding parameters admit sufficient diffusion and reaction of Al atoms, Fe-Al compound can generate at the whole interface adequately and form a thick continuous layer. Although Fe-Al compound forms strong combination, interfacial embrittlement will happen in thick continuous Fe-Al compound layer. So under the condition of too high preheat temperature of steel plate, too high temperature of aluminum liquid and too long bonding time, the interfacial shear strength is also small. Only when the bonding parameters admit moderate diffusion and reaction of Al atoms, for example, when the bonding parameters are 226 ℃ for preheat temperature of steel plate, 723 ℃ for temperature of aluminum liquid, 15.8s for bonding time, the interface of bonding plate can be made up of Fe-Al compound with suitable thickness. In this structure, the interfacial embrittlement is avoided and thus the interfacial shear strength is the largest. Fig. 5 shows the typical interface of the bonding plate with large interfacial shear strength. The left side is 08Al steel substrate. The right side is aluminum layer. The juncture of aluminum and steel substrate is the interface. It can be seen that the interface is made up of tooth-shaped Fe-Al compounds with suitable length. These Fe-Al compounds not only form strong combination but also avoid interfacial embrittlement. Therefore, the interfacial shear strength is large.

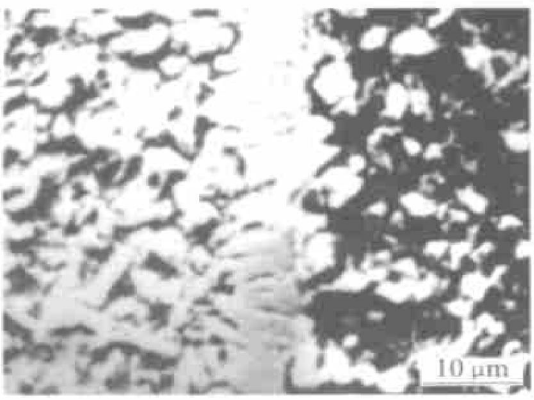

Fig. 5 Interface of bonding plate

4 CONCLUSIONS

1) The relationship between bonding parameters and interfacial shear strength in steel-aluminum solid to liquid bonding can be established by artificial neural networks perfectly.

2) The relationship established by artificial neural networks can be optimized with a genetic algorithm successfully. The optimum bonding parameters are 226 ℃ for preheat temperature of steel plate, 723 ℃ for temperature of aluminum liquid, 15.8s for bonding time, and the maximum interfacial shear strength of bonding plate is 71.6 MPa.

REFERENCES

[1] HUA Q, QI F P. Development of technique of hot-dip aluminusing for iron and steel parts [J]. Materials for Mechanical Engineering, 1995, 19(1): 32−36.

[2] LI C P, LIU X T. Structure analysis of hot impregnated Al-Si coating [J]. Acta Metallurgica Sinica, 1989, 25(5): 382−385.

[3] Eggeler G, Auer W, Kaescbe H. On the influence of silicon on the growth of the alloy layer during hot dip aluminizing [J]. J Mater Sci, 1986, 21: 3348−3353.

[4] Komatsu N. Investigation on the bonding of steel and aluminum [J]. J Jpn Met, 1981, 45: 416−420.

[5] GUO J, WU Y K. Investigation on mechanical properties and corrosion resistance of aluminum coated low carbon steels [J]. Materials for Mechanical Engineering, 1995, 19(5): 20−24.

[6] Dybkov V I. Interaction of 18Cr-10Ni stainless steel with liquid aluminum [J]. Journal of Materials Science, 1990, 25: 3615−3623.

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

[8] Psaltis D, Sideris A, Tamanmuya. Multilayered neural network controller [J]. IEEE Control Syst Mag, 1988, 8: 17−23.

[9] SONG R G, ZHANG Q Z, ZHANG B J. The application of artificial neural networks to the investigation of aging dynamics in 7175 aluminium alloys [J]. Materials Science & Engineering, 1995, C3: 39−43.

[10] ZHANG P, DU Y H. Artificial neural networks in steel-mushy aluminum pressing bonding [J]. Trans Nonferrous Metal Soc China, 2000, 10(2): 213−218.

[11] ZHANG P, DU Y H. Modeling and optimizing of steel and mushy Al-28Pb alloy bonding [J]. Trans Nonferrous Metal Soc China, 2001, 11(2): 239−243.

[12] QIAN W J, GU W G. Inhibitory action of Si on growth of interfacial compound layer during hot-dip aluminizing [J]. Acta Metallurgica Sinica, 1994, 30(9): 404−408.

(**Edited by LONG Huai-zhong**)