Relationship between solid fraction of slurry and property of steel/mushy Al-20Sn semi-solid bonding[①]

ZHANG Peng(张　鹏)[1], DU Yun-hui(杜云慧)[1], XING Shu-ming(邢书明)[1], ZHANG Li-zhong(张励忠)[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 slurry of Al-20Sn alloy was prepared using electromagnetic-mechanical stirring method. The bonding of steel/mushy Al-20Sn was conducted using casting rolling technique. The bonding parameters were 505 ℃ for preheat temperature of steel plate and 10 mm/s for rolling speed. The interfacial mechanical property and structure of steel/mushy Al-20Sn bonding plate were studied. The results show that the relationship between solid fraction of Al-20Sn slurry and interfacial shear strength of bonding plate is $S = 52.9 + 0.998 \varphi_s - 0.014\,4 \varphi_s^2$ (where S is interfacial shear strength, φ_s is solid fraction). The largest interfacial shear strength is 70.2 MPa when solid fraction is 34.6%. The interface of bonding plate is made up of Fe-Al compound and Fe-Al solid solution alternatively.

[Key words] bonding of steel/mushy Al-20Sn; solid fraction; interfacial shear strength; interfacial structure

[CLC number] TD 146.2   [Document code] A

1 INTRODUCTION

Steel/Al-20Sn bonding plate is the ideal material of neotype bearing[1~3]. Almost one million tons per year of this kind material are needed in machinery and automobile field[4~6]. Two kinds of techniques are usually adopted to process this bonding plate[7]. One is solid to solid bonding, that is, bonding of solid steel plate to solid Al-20Sn alloy plate. The other is solid to liquid bonding, that is, bonding of solid steel plate to liquid Al-20Sn alloy.

For solid to solid bonding, there mainly exist mechanical occlusion and only a little physical combination at the interface[8]. Therefore interfacial mechanical property is generally lower, usually only about 40 MPa. This limits the application of bonding plate greatly.

For solid to liquid bonding, there mainly exists metallurgical combination, which is the firmest one, at the interface[9]. However, the higher bonding temperature often results in a thick continuous Fe-Al compound (Fe_2Al_5 and $FeAl_3$) layer at the interface. This layer embrittles the interface to a certain extent[10]. So the interfacial mechanical property does not reach its own level, usually is about 60 MPa. Therefore, the development of new technique to eliminate the embrittlement at the interface becomes the focus in steel/Al-20Sn bonding field.

The embrittlement results from the stratification of Fe-Al compound. Therefore, only destroying the Fe-Al compound distribution can the embrittlement

be eliminated. Fe-Al compound is the result of Al atoms diffusion to steel substrate and reaction with Fe atoms[11]. If the concentration of Al atoms in steel substrate is not uniform, the distribution of Fe-Al compound will be different at the interface. In this work, the bonding of steel/mushy Al-20Sn was conducted. The aim of using Al-20Sn slurry is to create the uneven distribution of Al atoms in steel substrate and thus destroy the stratification of Fe-Al compound.

In this paper, the slurry of Al-20Sn is prepared using electromagnetic-mechanical stirring method. The relationship between solid fraction of Al-20Sn slurry and interfacial shear strength of bonding plate under the condition of 505 ℃ for preheat temperature of steel plate and 10 mm/s for rolling speed is determined. The interface of bonding plate is also studied.

2 EXPERIMENTAL

The materials used in this experiment were 1.2 mm thick 08Al steel plate and Al-20Sn (mass fraction, %) alloy.

The experimental procedures were as follows.

1) Treat the steel plate surface. Firstly defat and descale the surface to get fresh surface. Secondly immerse the surface 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. This flux layer could prevent the fresh surface from oxidizing.

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

2) Prepare Al-20Sn alloy slurry. Fig. 1 is the diagram of Al-20Sn slurry-making apparatus. It includes three main parts such as electromagnetic stirrer, uniform device and graphite crucible. Electromagnetic stirrer is made up of three couples of electric poles which distribute around the crucible evenly, its main action is to break up the arborescent crystal in the process of solidification by the circular motion of slurry. Its power is 10 kW. Uniform device is a specially-designed fluid director, it can move up and down by using an assistant electric device. Its main action is to change the centrifugal flow and gravity segregation of Sn in order to get Sn-distributing-uniformly Al-20Sn slurry. Graphite crucible is a temperature-adjusting container, there are holes in its wall evenly, these holes contain heaters and coolers so as to adjust the temperature of slurry. The process of making slurry was as follows: preheat the crucible up to 550 ℃ by using the heaters, pour alloy liquid of the 700 ℃ into the crucible, overlay the upper cover, inlet Ar gas through the gas pipe in order to prevent the alloy from oxidizing, switch on the electromagnetic stirrer and the uniform device, pump the cooling mediator into the coolers to cool the alloy to the required temperature. Switch on the heaters and adjust the current to keep the temperature stable. The precision of temperature was ±0.5 ℃. After a certain time, the uniform slurry with required solid fraction could be made.

3) Conduct the bonding of steel/mushy Al-20Sn. The experimental equipment is shown in Fig. 2. The length of pouring mouth is 200 mm. The diameter of roller is 320 mm. The preheat temperature of steel plate is 505 ℃. The precision of temperature is ±1 ℃. The rolling speed is 10 mm/s. The preci-

sion of speed is ±0.1 mm/s. The thickness of bonding plate is 2.5 mm.

4) Cut up the bonding plate into testing samples for mechanical experiment and SEM experiment using linear cutting method. Testing sample for mechanical experiment is shown in Fig. 3. Testing sample for SEM experiment was block of 10.0 mm × 10.0 mm × 2.5 mm; one side of this sample must be carefully ground, polished, eroded, cleaned and dried. The volume fraction of etching liquid was 0.5% HF, 1.5% HCl, 2.5% HNO_3 and 95.5% H_2O.

5) Conduct mechanical experiment to measure interfacial shear strength on universal material testing machine, and conduct SEM experiment to determine interfacial structure of bonding plate.

3   RESULTS AND DISCUSSION

3.1   Relationship between solid fraction and interfacial shear strength

According to experimental data, the relationship between solid fraction of Al-20Sn slurry and interfacial shear strength of bonding plate in steel/mushy Al-20Sn bonding is obtained (as shown in Fig. 4). After regressive analysis using nonlinear theory, the regressive equation is

$$S = 52.9 + 0.998 \varphi_s - 0.014 4 \varphi_s^2 \qquad (1)$$

where S is interfacial shear strength, φ_s is solid fraction. The regression coefficient R_l is 0.979 4. This illustrates that regressive Eqn. 1 has built a correct relationship between solid fraction of Al-20Sn slurry and interfacial shear strength of bonding plate. Let the derivative of Eqn. 1 equal to nought, the condition for the largest interfacial shear strength is obtained as $\varphi_s = 34.6\%$, and the corresponding largest interfacial shear strength is 70.2 MPa.
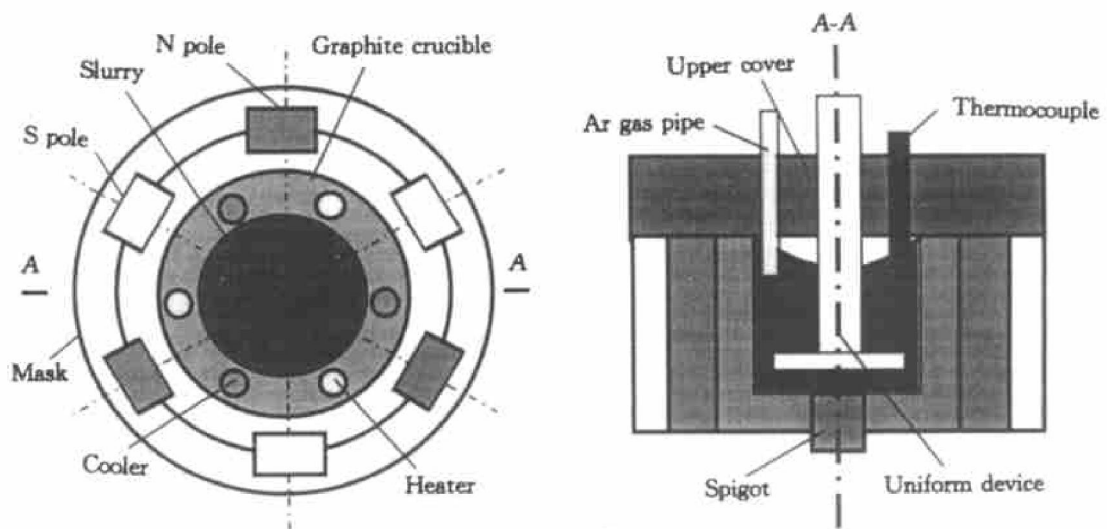
3.2   Interfacial structure of bonding plate

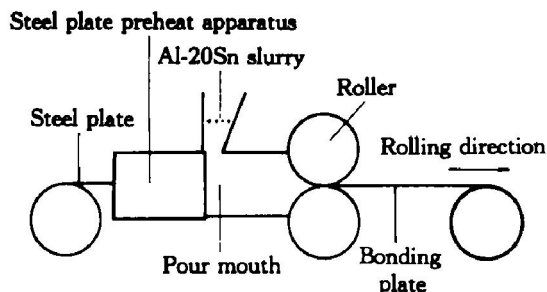**Fig. 1**   Diagram of Al-20Sn slurry-making apparatus

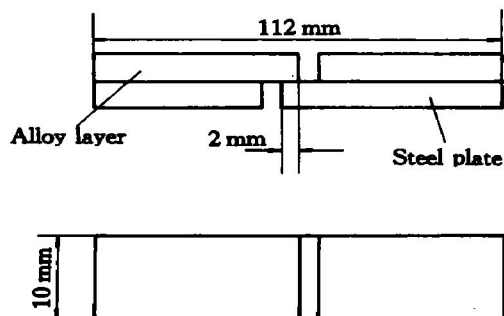**Fig. 2**   Sketch of steel/mushy Al-20Sn bonding

Fig. 3   Testing sample for interfacial
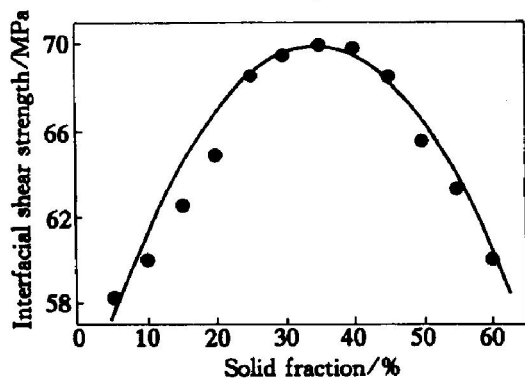shear strength

Fig. 4   Solid fraction vs interfacial shear strength

Fig. 5 is the typical SEM image of interface of the bonding plate. The right side is 08Al steel substrate. The left side is Al-20Sn alloy layer. In Al-20Sn alloy layer, the white round parts are the primary solid particles and the dark round parts are Sn particles. It can be seen that not only the primary solid particles but also Sn particles distribute rather evenly in Al-20Sn alloy layer. The juncture of steel substrate and Al-20Sn alloy layer is the interface. It can be seen that the interface is made up of the regions such as 1, 2 and 3. The results of composition analysis show that regions 1 and 3 are made up of Fe-Al compound and region 2 is made up of Fe-Al solid solution whose aluminum content is less than 3.5%. Therefore the interface of steel/mushy Al-20Sn bonding plate is made up of Fe-Al compound and Fe-Al solid solution alternatively. There is no continuous Fe-Al compound layer at the interface.
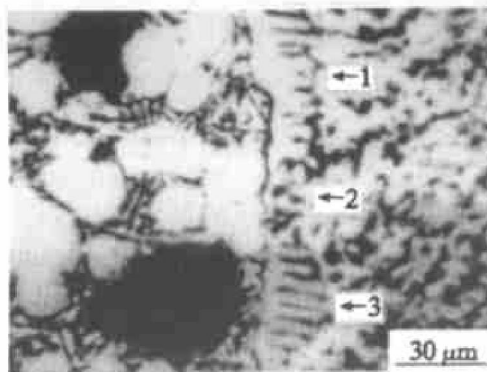

Fig. 5   Interface of bonding plate

3.3   Discussion

For the bonding of steel/mushy Al-20Sn, when Al-20Sn slurry contacts with the surface of steel plate, the primary solid particles and liquid Al-20Sn alloy in the slurry contact with steel substrate in some proportion respectively. The liquid Al atom has higher energy, its diffusion and reaction capability is bigger[12]. So there exists severe diffusion and reaction at the place where liquid Al-20Sn alloy contacts with steel substrate, which generates the Fe-Al compound, and the interfacial structure is just the same as that of solid to liquid bonding. However, the solid Al atom has lower energy, its diffusion and reaction capability is smaller. Furthermore, the contact of primary solid particles with steel plate is not as close as that of liquid Al-20Sn alloy with steel plate, so there exists little diffusion at the place where primary solid particles contact with steel substrate, here only generates the Fe-Al solid solution. Thus the interface of steel/mushy Al-20Sn bonding plate is made up of Fe-Al compound and Fe-Al solid solution alternatively.

To steel/mushy Al-20Sn bonding, the smaller the solid fraction of Al-20Sn slurry, the more the diffusion of Al atom in steel substrate, and the more the Fe-Al compounds at the interface. When solid fraction is 0, the bonding becomes solid to liquid bonding. On the contrary, the larger the solid fraction, the less the diffusion of Al atom, and the more the Fe-Al solid solution. When solid fraction is 100%, the bonding becomes solid to solid bonding. Therefore, when solid fraction is too small, the interface is made up of Fe-Al compound mainly. The embrittlement happens just as solid to liquid bonding. However, with increasing solid fraction, the quantity of Fe-Al compound decreases but that of Fe-Al solid solution increases gradually at the interface. Fe-Al compound forms strong metallurgical combination, and Fe-Al solid solution forms weak combination. Nevertheless, it is this Fe-Al solid solution that destroys the thick continuous Fe-Al compound layer into an Fe-Al compound net and decreases the embrittlement. Therefore, when solid fraction is smaller than 34.6%, the interfacial shear strength increases grad-

ually with increasing solid fraction (as shown in Fig. 4). Furthermore, when solid fraction is 34. 6%, the interface is made up of Fe-Al compound and Fe-Al solid solution in moderate proportion and the interfacial shear strength reaches to the largest value. But when solid fraction is larger than 34. 6%, with increasing solid fraction, the weak combination of Fe-Al solid solution becomes the dominant form of combination at the interface gradually, thus the interfacial shear strength decreases gradually at this condition (as shown in Fig. 4).

4 CONCLUSIONS

1) For the bonding of steel/ mushy Al-20Sn, the interface of bonding plate is made up of Fe-Al compound and Fe-Al solid solution alternatively. This new structure eliminates the interfacial embrittlement, so the interfacial mechanical property of bonding plate is improved. This bonding method can be expected to become a good technology for processing steel/ Al-20Sn bonding plate.

2) Under the conditions of 505 ℃ for preheat temperature of steel plate and 10 mm/ s for rolling speed, the relationship between solid fraction of Al-20Sn slurry and interfacial shear strength of bonding plate is $S = 52. 9 + 0. 998 \varphi_s - 0. 014 4 \varphi_s^2$ where S is interfacial shear strength, φ_s is solid fraction. The reasonable solid fraction for the largest interfacial shear strength 70. 2 MPa is 34. 6%.

[REFERENCES]

[1]   Davis J R. ASM speciality handbook: aluminum and aluminum alloys[M]. Materials Park, OH: ASM International Publications, 1993. 156– 158.

[2]   Mengucci P, Abis S. Electron microscopy characterization of Al-Sn metal-metal matrix composites[J]. Journal of Alloy and Compound, 1994, 215(11): 309– 313.

[3]   Merkwitz M, Hoyer W. Liquid-liquid interfacial tension in the demixing metal system Al-Pb and Al-Sn[J]. Z Metallkd, 1999, 90(5): 363– 368.

[4]   Zhang P, Du Y H. Application of artificial neural networks to investigation on thickness of intermetallic layer under solid-liquid pressure bonding of steel and aluminum [J]. Acta Metall Sin, 1997, 10(6): 523– 526.

[5]   Bishop D P, Cahoon J R. Diffusion-based microalloying of aluminum alloys by powder metallurgy and reaction sintering[J]. J Mater Sci, 1998, 33: 3927– 3932.

[6]   Zhang P, Du Y H. The influence of solid fraction on gravity segregation of Sn in Al-20Sn alloy casting[J]. J Mater Sci Technol, 2000, 16(6): 605– 609.

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

[8]   GUO J, WU Y K. Investigation on mechanical properties and corrosion resistance of aluminum coated low carbon steels [J]. Mater Mech Eng, (in Chinese), 1995, 19(5): 20– 24.

[9]   Dybkov V I. Interaction of 18Cr-10Ni stainless steel with liquid aluminum[J]. J Mater Sci, 1990, 25: 3615 – 3624.

[10]   ZHANG P, DU Y H. Immersing treatment of steel plate surface in steel-aluminum solid to liquid bonding [J]. J Uni Sci Technol Beijing, 1999, 6(1): 57– 60.

[11]   WANG Z T, TIAN R Z. Handbook of Aluminum Alloy and its Forming, (in Chinese) [M]. Changsha: Central South University of Technology Press, 1988. 103 – 105.

[12]   Fang J X. Solid Physics, (in Chinese) [M]. Shanghai: Shanghai Science and Technology Press, 1980. 170 – 175.

(Edited by HUANG Jin-song)