Article ID: 1003-6326(2003)05-1141-04

Effect of rolling on interfacial property of steel/mushy Al-20Sn bonding plate①

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 110004, China;
4. Anshan Automobile Fittings Factory, Anshan 114014, China)

Abstract: The rolling treatment of steel/mushy Al-20Sn bonding plate was conducted under different relative reduction at room temperature. The effect of room-temperature rolling on interfacial mechanical property of bonding plate was studied. The results show that, for steel/mushy Al-20Sn bonding plate which consists of 1.2mm-thick 08Al steel plate and 2.0mm-thick Al-20Sn layer, the relationship between interfacial shear strength and relative reduction is $S = 70.1 + 5.48r - r^2$ (S is interfacial shear strength, r is relative reduction). When the relative reduction is 2.74%, the largest interfacial shear strength 77.6 MPa can be obtained.

Key words: rolling; relative reduction; interfacial shear strength
CLC number: TD 146 **Document code:** A

1 INTRODUCTION

Steel/Al-20Sn bonding plate is ideal material for neotype bearing[1]. It is widely used in the fields such as machinery, automobile, etc[2-5]. For this bonding plate, two things are very important. One is the distribution of Sn particles in Al-20Sn layer, the other is the interfacial shear strength. The former determines the life of bonding plate. The latter determines the safety of bonding plate. The evener the distribution of Sn particles in Al-20Sn layer, the longer the usage life of bonding plate. The larger the interfacial shear strength, the safer the usage of bonding plate.

Steel/mushy Al-20Sn bonding plate is prepared using steel plate and Al-20Sn slurry. Bonding with Al-20Sn slurry not only easily realizes the uniform distribution of Sn particles in Al-20Sn layer but also forms a new type of interfacial structure which is made up of Fe-Al compound and Fe-Al solid solution alternatively[6, 7]. This new type interface eliminates the interfacial embrittlement at the interface which is made up of Fe-Al compound entirely. So steel/mushy Al-20Sn bonding plate is very good.

It is well known that, for bonding of different metals, subsidiary stress will generate at the interface in the process of cooling after bonding because of the difference of physical characters[8]. Similarly, there exists subsidiary stress at the interface of steel/mushy Al-20Sn bonding plate. This subsidiary stress can decrease the interfacial mechanical property of bonding plate. Therefore, the interfacial mechanical property can be increased by eliminating the subsidiary stress.

At present, the method of eliminating interfacial subsidiary stress is annealing[9]. In the process of annealing, the atoms in subsidiary stress region can acquire enough energy to move from higher energy equilibrium position to lower energy equilibrium position and thus eliminate the interfacial subsidiary stress. However, for steel/mushy Al-20Sn bonding plate, annealing is not very ideal. Since continuous Fe-Al compound layer may form at the interface in the process of annealing, and it can embrittle the interface[10, 11]. So new technique to eliminate interfacial subsidiary stress of steel/mushy Al-20Sn bonding plate must be developed.

In this paper, the room-temperature rolling technology is used to eliminate the interfacial subsidiary stress of steel/mushy Al-20Sn bonding plate and the effect of rolling on interfacial shear strength of bonding plate is determined.

2 EXPERIMENTAL

The experimental material was steel/mushy Al-

① **Foundation item:** Project(50274047) supported by the National Natural Science Foundation of China and project (715-009-060) supported by the National Advanced Materials Committee of China
Received date: 2002-11-12; **Accepted date:** 2003-03-24
Correspondence: ZHANG Peng, Professor; Tel: +86-10-51682226, E-mail: zhangp9@263.net

20Sn bonding plate which was made up of 1.2 mm-thick 08Al steel plate and 2.0 mm-thick Al-20Sn layer.

The experimental procedures were described as follows.

1) Conduct room-temperature rolling. At room temperature, the steel/mushy Al-20Sn bonding plates were rolled under different relative reduction $\Delta h/H$ on precision rolling mill. In relative reduction $\Delta h/H$, Δh was the D-value between the thickness before rolling H and that after rolling h.

2) Cut the bonding plate into testing samples for mechanical experiment using linear cutting method. The dimensions of testing sample for mechanical experiment are shown in Fig. 1.

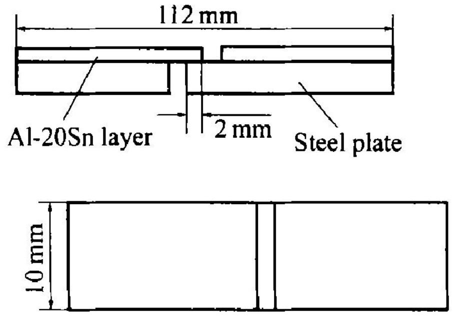

Fig. 1 Testing sample

3) Conduct mechanical experiment to measure interfacial shear strength using universal material testing machine.

3 RESULTS AND DISCUSSION

3.1 Relationship between relative reduction and interfacial shear strength

According to the experimental data, the relationship between the relative reduction of rolling and the interfacial shear strength of bonding plate is got (as shown in Fig. 2). After regressive analysis using nonlinear theory, the regressive equation is got as:

$$S = 70.1 + 5.48r - r^2 \quad (1)$$

where S is the interfacial shear strength, r is the relative reduction. The regression coefficient R_1 is 0.998 21. This illustrates that regressive equation (1) has built a correct relationship between the relative reduction of rolling and the interfacial shear strength of bonding plate. Let the derivative of Eqn. (1) equal to nought, the condition for the largest interfacial shear strength is got: $r = 2.74\%$, and the corresponding largest interfacial shear strength is 77.6 MPa. This value is nearly 10 MPa larger than that of the original bonding plate.

3.2 Analysis and discussion

For steel/mushy Al-20Sn bonding plate, the expansion coefficient of Al-20Sn layer is much bigger than that of steel plate. Therefore, in the process of

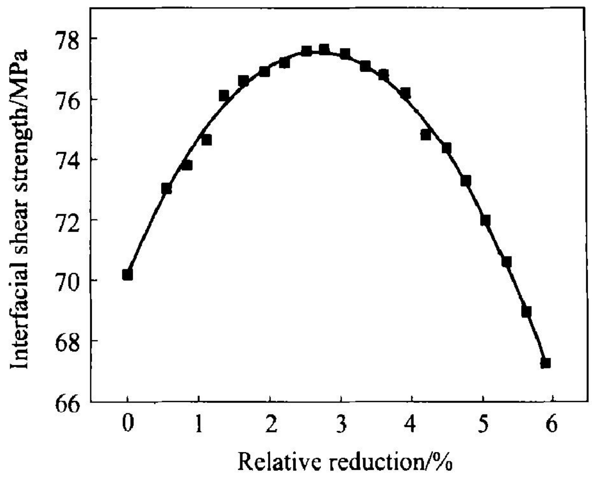

Fig. 2 Relationship between relative reduction and interfacial shear strength

cooling after bonding, the shrinkage of Al-20Sn layer is much greater than that of steel plate. Since the strength of Al-20Sn layer is much smaller than that of steel plate, the shrinkage of Al-20Sn layer is restricted greatly by steel plate. Thus there exists crystal lattice distortion region in both sides of Al-20Sn and steel. Fig. 3 shows the cross section schematic diagram of bonding plate, in which EF is the interface, $ACEFDB$ is Al-20Sn layer, $EGIJHF$ is steel plate, $EGHF$ is the crystal lattice distortion region of steel plate, and $CEFD$ is the crystal lattice distortion region of Al-20Sn layer. It can be seen that, the closer the position from the interface is, the more severe the crystal lattice distortion generates, and the most severe the crystal lattice distortion generates at the interface. Therefore the largest subsidiary normal stress which is determined by crystal lattice distortion generates at the interface. In Al-20Sn side, the subsidiary normal stress is subsidiary normal tension stress. In steel side, the subsidiary normal stress is subsidiary normal compression stress.

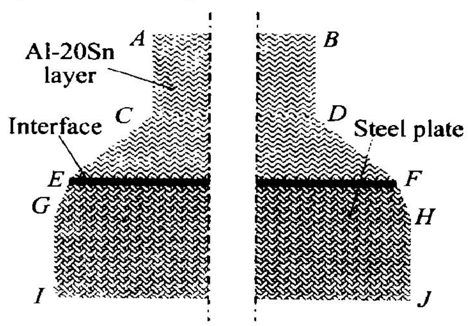

Fig. 3 Cross section of bonding plate

For Al-20Sn side at the interface, E and F are two free edges where no subsidiary normal stress exists. Therefore, before the subsidiary normal tension stress reaches the largest value (as shown in Fig. 4, c—c' region), there are two transition

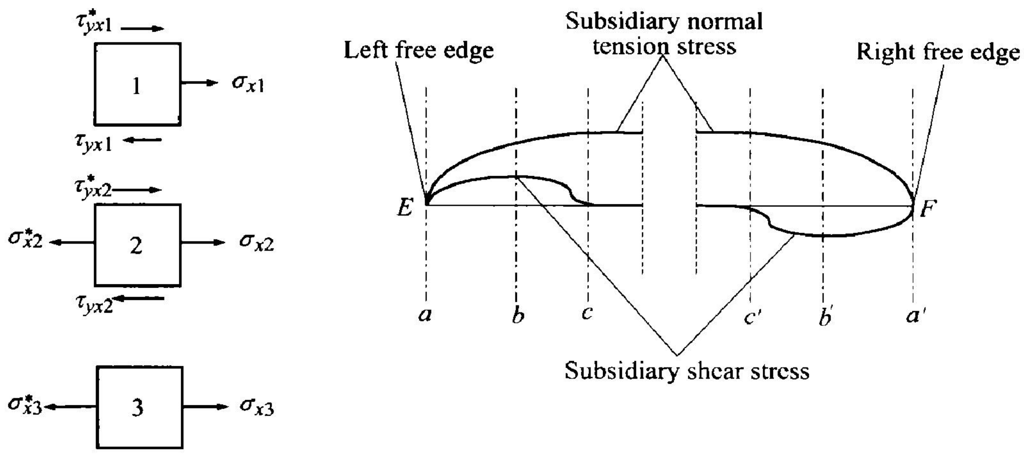

Fig. 4 Subsidiary stress in Al-20Sn side

regions of subsidiary normal tension stress (as shown in Fig. 4, a — c and c' — a' regions) at the interface. In a — c region, the subsidiary normal tension stress increases gradually to the largest value from a to c along horizontal direction. If a square unit is got at a, the stress diagram in x dimension (horizontal direction) will be shown as unit 1 in Fig. 4. The left edge is free one, where no stress exists. The right edge is the inner one where a subsidiary normal tension stress σ_{x1} exists. From force balance differential equation[12]

$$\frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \sigma_x}{\partial x} = 0 \qquad (2)$$

it can be got that, if $\partial \sigma_x / \partial x \neq 0$, $\partial \sigma_{yx} / \sigma_y \neq 0$, there exist subsidiary shear stresses τ^*_{yx1} and τ_{yx1}, and τ^*_{yx1} is smaller than τ_{yx1}. τ_{yx1} is the subsidiary shear stress at the interface. At c or in c — c' region, the subsidiary normal tension stress reaches the largest value (as shown in Fig. 4, unit 3), $\sigma_{x3} = \sigma^*_{x3} = \sigma_{max}$, that is, $\partial \sigma_x / \partial x = 0$, from Eqn. (2), then $\partial \sigma_{yx} / \partial_y = 0$, that is, $\tau^*_{yx1} = \tau_{yx} = 0$. Therefore, there is only subsidiary normal tension stress and no subsidiary shear stress. From a to c, the subsidiary shear stress changes from 0 to some value then back to 0 again. Therefore, in a — c region, there must be a largest subsidiary shear stress, just as unit 2 at b in Fig. 4, $\tau_{yx2} = \tau_{max}$. In c' — a' region, the right edge is free one. The distribution of subsidiary stress is the opposite of that in a — c region (as shown in Fig. 4). Among the subsidiary stresses at the interface, it is the largest subsidiary shear stress that is vital for steel/ mushy Al-20Sn bonding plate. It can couple with the external shear stress and the sum breaks up the bonding of steel plate and Al-20Sn layer. Therefore, if the largest subsidiary shear stress is eliminated, the interfacial shear strength of steel/ mushy Al-20Sn bonding plate can be increased.

The largest subsidiary shear stress is the result of crystal lattice distortion which results from the shrinkage difference between steel plate and Al-20Sn layer in the process of cooling after bonding. Therefore, only the shrinkage difference between steel plate and Al-20Sn layer is removed can the largest subsidiary shear stress be eliminated. For steel/ mushy Al-20Sn bonding plate, the yield strength of Al-20Sn layer is much smaller than that of steel plate. If a certain external force, which is bigger than the yield strength of Al-20Sn layer but smaller than that of steel plate, exerts on the bonding plate, Al-20Sn layer will produce plastic elongation but steel plate will not. This will result in the deformation difference between steel plate and Al-20Sn layer. If this deformation difference equals to the shrinkage difference between steel plate and Al-20Sn layer, the largest subsidiary shear stress at the interface can be eliminated. This is the basic thought of the room-temperature rolling technology.

In room-temperature rolling, when the relative reduction is in the range of 0 - 2.74% (as shown in Fig. 4), the plastic elongation of Al-20Sn layer increases gradually with increasing relative reduction and the shrinkage difference between steel plate and Al-20Sn layer reduces constantly. Therefore, the interfacial shear strength increases gradually with decreasing the largest subsidiary shear stress at the interface. When the relative reduction is about 2.74%, the plastic elongation of Al-20Sn layer completely removes the shrinkage difference between steel plate and Al-20Sn layer, and the largest subsidiary shear stress at the interface is eliminated. Therefore, the interfacial shear strength reaches its largest value. When the relative reduction is more than 2.74%, the plastic elongation of Al-20Sn layer not only removes the shrinkage difference between steel plate and Al-20Sn layer but also results in new elongation difference between steel plate and Al-20Sn layer. This new elongation difference also results in a new largest subsidiary shear stress at the interface. The bigger the relative reduction is, the larger the new elongation difference will be, and the larger the new largest subsidiary shear stress is. Therefore, the interfacial shear strength decreases gradually with increasing relative reduction.

3.3 Comparison with annealing

The annealing tests were conducted at 350, 400, 450 and 500 ℃ for 6, 12 and 24 h, respectively, and the cooling manner was cooling with furnace. The results show that the highest interfacial shear strength is 71 MPa which is much lower than that after room-temperature rolling. Fig. 5 shows the typical interface of steel/mushy Al-20Sn bonding plate after annealing. The right side is Al-20Sn layer, the left side is steel substrate. The juncture of Al-20Sn layer and steel substrate is the interface. It can be seen that the interface becomes a thick Fe-Al compound layer. If Fe-Al compound becomes thick layer, the interfacial embrittlement inevitably generates. Although annealing eliminates the interfacial subsidiary stress, the thick Fe-Al compound layer embrittles the interface. Therefore the highest interfacial shear strength after annealing is much lower than that after room-temperature rolling. It can be said that room-temperature rolling is a new and good method to eliminate the interfacial subsidiary stress and thus increase the interfacial mechanical property.

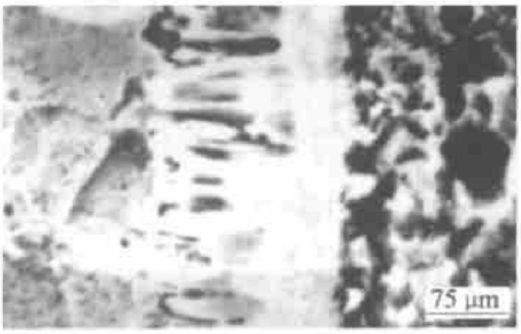

Fig. 5 Interface after annealing

4 CONCLUSIONS

1) The room-temperature rolling technology is a new and good method to eliminate the interfacial subsidiary stress and increase the interfacial mechanical property of steel/mushy Al-20Sn bonding plate.

2) For steel/mushy Al-20Sn bonding plate which is made up of 1.2 mm-thick 08Al steel plate and 2.0 mm-thick Al-20Sn layer, the relationship between interfacial shear strength and relative reduction is

$$S = 70.1 + 5.48r - r^2$$

where S is interfacial shear strength, r is relative reduction. When the relative reduction is 2.74%, the largest interfacial shear strength 77.6 MPa is got.

REFERENCES

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

[2] ZHANG D G. Developing the composite technology according to the state and need of our country[J]. Mater Eng, 1994, 3: 1－4. (in Chinese)

[3] Davis J R. ASM Speciality Handbook: Aluminum and Aluminum Alloys[M]. Materials Park, OH: ASM International Publications, 1993. 156－158.

[4] Patty G. The Development of Composite Material [M]. Beijing: Science Press, 1984. 125－131. (in Chinese)

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

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

[8] ZHANG G D. Interface problem of metal matrix composites[J]. Chinese J Mater Resarch, 1997, 11(6): 649－656.

[9] CUI Z Z. Metallurgy and Heat Treatment[M]. Beijing: China Machine Press, 1989. 145－168. (in Chinese)

[10] HUA Q, QI F P. Development of technique of hot-dip aluminizing for iron and steel parts[J]. Mater Mech Eng, 1995, 19(1): 32－36. (in Chinese)

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

[12] ZHAO Z Y. Plastic Forming of Metal [M]. Beijing: Metallurgical Industry Press, 1987. 58－69. (in Chinese)

(Edited by YUAN Sai-qian)