[Article ID] 1003 - 6326(2000)05 - 0625 - 06

Interfacial bonding strength of Al-Pb bearing alloy strips and hot dip aluminized steel sheets by hot rolling①

LIU Yong-bing(刘勇兵), AN Jian(安 健), SUN Da-ren(孙大仁)
(Department of Material Science and Engineering, Jilin University of Technology,
Changchun 130025, P.R.China)

[Abstract] Al-Pb alloy strips and hot dip aluminized steel sheets were successfully bonded together by hot rolling, and the interfacial bonding strengths after rolling was evaluated by a new method. The bonding modes were studied by optical and scanning electron microscope and energy dispersive X-ray analysis, and the effects of the thickness of the intermetallic layers and the Si content in hot dip aluminized layers on the interfacial bonding strength were also investigated respectively. It is found that the hot dipped steel and Al-Pb alloy are bonded through blank interface bonding and block interface bonding, and the total bonding strength mainly depends on that of blank interfaces and the fraction of blank interfaces. There is a linear relationship between the total bonding strength F and the fraction of blank interfaces K_b. The bonding strength varies with the Si content in the hot dipped aluminized layers on the surface of steel sheets, the fraction of blank interfaces and the rotation of the intermetallic blocks.

[Key words] Al-Pb alloy; interface; hot rolling; interfacial bonding strength
[CLC number] TG113.1 **[Document code]** A

1 INTRODUCTION

Al-Pb alloys as a newly developed bearing material for automobiles have attracted lot of attention due to their outstanding properties such as wear resistance, anti-seizure, compatibility, fatigue resistance and low price[1~4]. However, the fabrication of as-cast Al-Pb alloy possesses serious problems of the wide density difference between Al and Pb (the density of Al and Pb are 2.7 g/cm^3 and 11.34 g/cm^3 respectively) and the mutual immiscibility for lead contents greater than 1.5% at temperature above 931.5 K[5]. Therefore, as-cast Al-Pb bearing alloys are hard to be prepared by conventional casting methods. Most of Al-Pb bearing alloys are made by powder metallurgy. But these difficulties do not shake confidence in the fact that Al-Pb alloys are the mainstream of future development for aluminum based bearing alloys. Researchers such as Mohn, Agarwala and Ray et al overcame those metallurgical difficulties in fabrication of Al-Pb alloys by means of stir-casting, and studied the friction and wear characteristics of as-cast Al-Pb alloy[1,3,4]. Ingots with Pb particles distributed uniformly in the matrix of Al alloy were cast by authors[6,7], and were rolled into strips 60 mm in width and 1.2 mm in thickness.

Conventional techniques of producing bimetallic strips are to bond Al alloys and steel together by cold rolling. However, the existing cold bonding technique presents problems such as low initial bonding strength in interface region, extraordinarily high percent of plastic deformation in one pass (about 70% deduction)[8] in order to ensure a good bonding quality, the rolling force sometimes exceeding the load capability of conventional mills, and great difficulty in further deformation owing to heavy work hardening of bimetallic strips.

If the technique of hot roll bonding is employed in an environment condition without protective air, the interfacial bonding of the bimetallic strips is very weak because of the fragile oxidation layer formed on the steel sheets. While the above disadvantages can be overcome by using hot dipped aluminized steel sheets as material of steel-back owing to the sufficient oxidation resistance of Al top coat layer on the surface of steel-back at elevated temperatures. Other advantages include low deformation resistance during hot rolling, high initial bonding strength and lightly work hardening. The purpose of this study is to investigate the combination modes of interface bonding and factors affecting bonding strength of Al-Pb alloy strips and hot dip aluminized steel sheets by hot rolling.

2 EXPERIMENTAL

2.1 Preparation of hot dipped aluminum sheets of steel

The steel sheets with composition (mass fraction, %) of Fe-0.09%C-0.40%Mn-0.0220%P-0.0014%S-0.04%Al were cut into a dimension of 75 mm × 20 mm × 1.5 mm. Prior to hot dip aluminizing, the steel sheets were pretreated through some process

---

① **[Foundation item]** Project (1999018513) supported by the National Doctorate Program Fund of the Education Ministry of China
[Received date] 1999 - 09 - 06; **[Accepted date]** 2000 - 07 - 03

such as degreasing, rust removing, rinsing, fluxing and drying. To obtain various thickness of the intermetallic layers, the specimens were immersed in melt baths of pure aluminum and Al-Si alloys with contents of 2 %Si and 6 %Si at 700 ℃ for various times of 0.5, 1, 2, 4 min. The thickness of Al and Al-Si alloys top coat layer and the intermetallic layer formed in melt bath were measured via optical microscope.

2.2 Preparation of bonded specimen and method of evaluating interfacial bonding strength

The Al-Pb alloy strips with a composition of Al-4 %Si-1 %Cu-0.5 %Mg-0.4 %Mn-1 %Sn-10 %Pb were cut into a dimension of 75 mm × 20 mm × 1.2 mm, and polished with emery paper until 1.10 mm in thickness left. The surface of hot dip aluminized steel sheets were also smoothed with emery paper, on which the Al or Al-Si top coat layers were partly removed and left about 30 μm in thickness, thus the steel sheets were 1.6 mm thick. Prior to hot rolling, a little part of surface from one end of an aluminized steel sheet facing Al-Pb alloy strip was smeared with graphite. Thus, the interface with graphite between Al-Pb alloy and hot dip aluminized steel sheets can not be rolled together tightly. One of the Al-Pb alloy strips was located in between steel sheets and heated in furnace at 400 ℃ for 30 min, then immediately rolled together with a deduction of 38 % to make a tri-metallic plate. The tri-metallic plate was then annealed at 400 ℃ for 30 min. After that, two u-shape-like grooves with 1.5 mm in width and 0.7 mm in depth were machined across both flank surfaces 20 mm away from the other end of the tri-metallic plate. The part under the grooves was pressed tightly by a pair of steel jaws and the interface with graphite was torn to the place where the u-shape-like grooves located, but could not reach beyond them because of the state of pressing beyond the grooves. Finally two torn parts were bent outwardly around an angle of nearly 90 degrees, the specimen took the shape as sketched in Fig.1. To measure the bonding strength, one end of the specimen was hold tightly while the other end was loaded. The loads were added step by step, and the minimum step value of load was 4.9 N, until the unsteady fracture occurred along the bonded interface. The fracture value then was used as the bonding strength of the interface. This method is similar in principle to that used by others[8] but much closer to the rolled state.

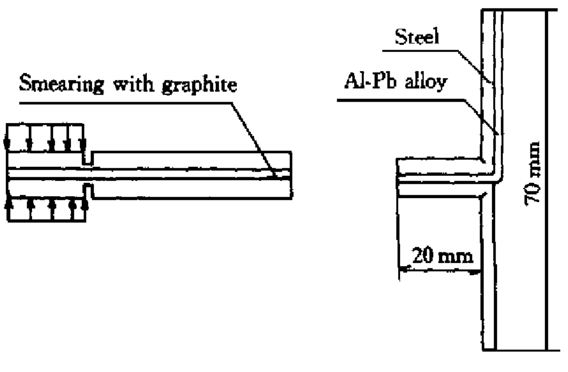

Fig.1 Schematic diagram of preparing bonded specimen

2.3 Observation of microstructure of hot dip aluminized layers and bonded interfaces

A Nikon optical microscope was used to observe the microstructure of hot dip aluminized layers, and to measure the thickness of Al or Al-Si top coat layers and the intermetallic layers adjacent to steel substrate. Jax-840 SEM and Oxford IsIs-33 EDX were employed to investigate the microstructure and distribution of alloying elements at bonding interface.

3 RESULTS AND DISCUSION

3.1 Morphology and thickness of hot dip aluminized layer

The hot dip aluminized layer can be divided into two layers as shown in Fig.2. The outer layer is the Al or Al-Si alloy top coat layer with almost the same composition as melt bath in which the specimens are dipped. Below the outer layer is the intermetallic layer. In the case of a pure aluminum bath, the intermetallic layer mainly consists of brittle and thick Fe_2Al_5, which has a "tongue-like" shape penetrating into the steel substrate. In the case of an Al-Si bath, the boundary between the intermetallic layer and the steel substrate is smoother than the former. It is observed clearly that the thickness of the intermetallic layer decreases with increasing Si content. The results above were also reported by previous observation[9], indicating that Si has evident effect on restriction in growth of the intermetallic layer. The variation in thickness of the intermetallic layers with dipping time is illustrated in Fig.3, showing the thickness of intermetallic layers increasing with dipping time.

3.2 Bonding strength of interface

The variation in bonding strength with dipping time is represented in Fig.4. It is noted that the bonding strength for all the hot dipped Al and Al-Si alloys increases with increasing time from 0.5 to 2 min, decreases beyond that. In fact, the dipping time has no effect on the structure and the morphology of the intermetallics but only affects the thickness of intermetallic layer in these experiment situations. Therefore, the relationship between bonding strength and intermetallic thickness is more direct than that between bonding strength and dipping time. Fig.5 shows the variation in bonding strength with the thickness of the intermetallic layer. It is observed that the bonding strength for both hot dipped Al and

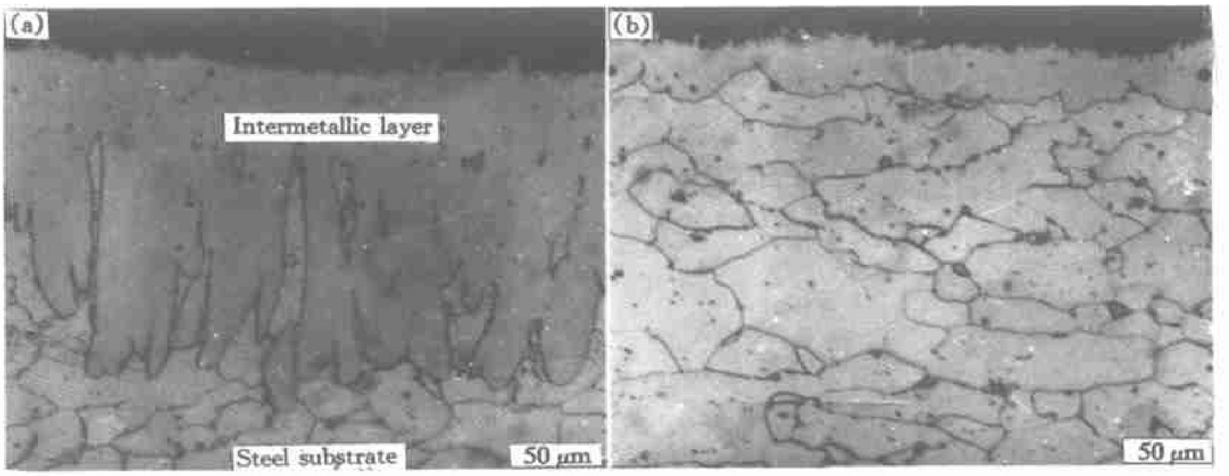

Fig.2 Photomicrographs of hot dip aluminized steel sheets (for 2 min)
(a) —Pure Al; (b) —Al-2 %Si

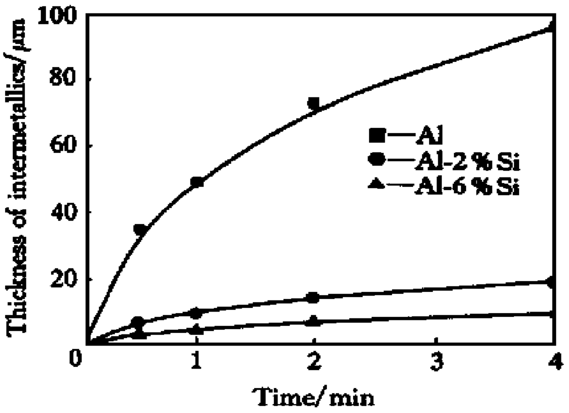

Fig.3 Thickness of intermetallic layer vs dipping time

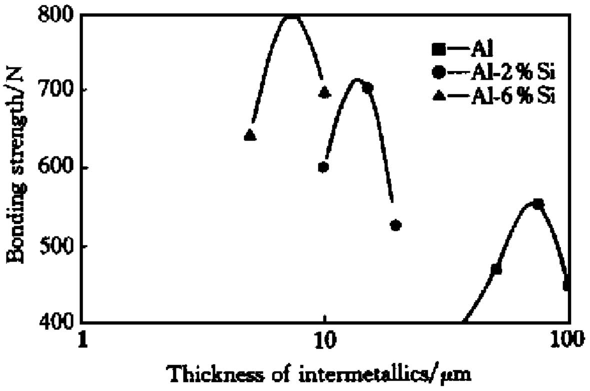

Fig.5 Bonding strength vs thickness of intermetallic layers

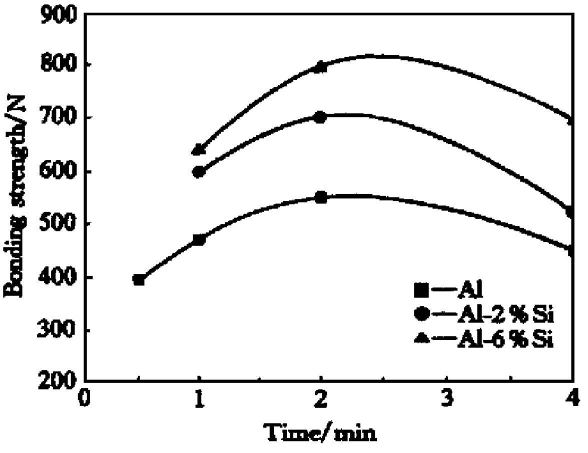

Fig.4 Bonding strength vs dipping time

Al-Si alloys varies in the same principle of increasing with increasing thickness of the intermetallic layer initially until a certain thickness of the intermetallic, then decreasing beyond that.

3.3 Interfacial bonding modes

Fig.6(a) is the lateral section photomicrograph of the bonded specimen. It clearly shows that during rolling, the intermetallic layer can not elongate in the direction of rolling with steel substrate because of its brittleness, but breaks into similarly sized blocks and u-shape-like blanks perpendicular to rolling direction form between them. Fig.6(b) is the photograph (SEM) of fractured interface on steel side. It is noted that the blanks crossing from one side to the other side on the steel sheet surface are parallel to each other, while the intermetallics breaks into blocks. Meanwhile, the Al-Pb alloy and the Al or Al-Si top coat layer elongating with rolling are squeezed into blanks between the broken intermetallic blocks. At the smooth bottom of u-shaped blanks, two fresh metals cold weld together tightly. Thus, part of Al-Pb alloy is bonded with aluminum layer above the intermetallic blocks, and the rest is bonded with the squeezed aluminum filling the blanks between the broken intermetallic blocks. Meanwhile, part of Al top coat layer is bonded with intermetallic blocks and the rest bonded with steel substrate at the bottom of blanks. Therefore, two different kinds of bonded interfaces are produced, i.e. Al-Pb alloy/Al top coat layer

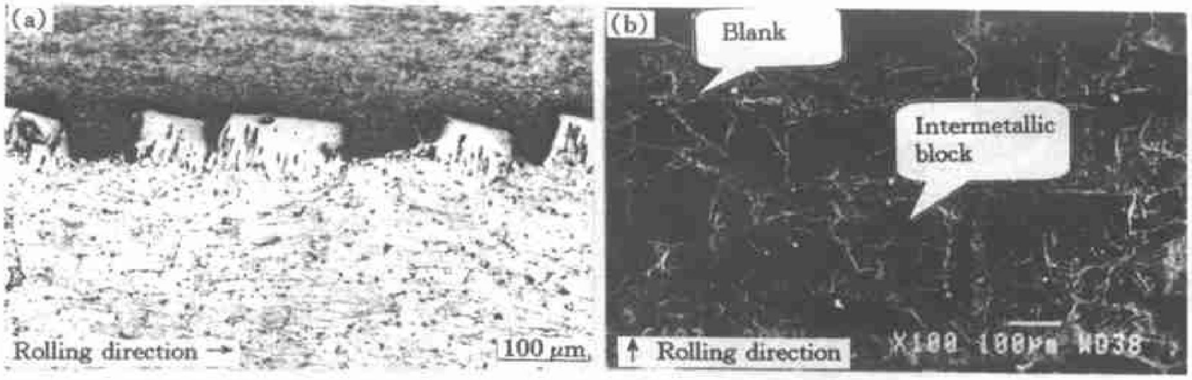

Fig.6 Microstructure of bonding interface
(a) —Lateral section photomicrograph; (b) —Fractured interface on steel side (SEM)

interface and Al top coat layer/intermetallic blocks and steel substrate interface. The EPMA analysis of lead mapping revealed that there was no trace of lead on the fractured interface on the steel side, indicating that the interface fractured between the steel substrate and the Al layer in the blank interface region, and on the top of broken blocks between the intermetallic blocks and the Al layer in the block interface region. Therefore the former interfacial bonding strength is greater than that of the later. The fracture occurs along the weaker interface, i.e. Al layer/intermetallic blocks and steel substrate interface. Thus the fractured interface is composed of block interfaces between Al and intermetallic blocks and blank interfaces between Al and steel substrate. Obviously the total bonding strength depends on that of these two different parts of fractured interfaces, i.e. blank interfacial bonding strength and block interfacial strength. The stronger one will affect the total strength considerably. The fraction of these two different parts of interface can be represented as following equations:

$$K_b = l_b / l \qquad (1)$$

$$K_c = l_c / l \qquad (2)$$

$$K_b + K_c = 1 \qquad (3)$$

where K_b is the fraction of blank interfaces between the intermetallic blocks, K_c is the fraction of block interfaces on the top of the intermetallic layer, l is the total length of the interface, l_b is the length of blank interfaces and l_c is the length of block interfaces in the direction of rolling. In order to measure l, l_b and l_c, the following equations are used

$$l = l_b + l_c \qquad (4)$$

$$l_b = \sum_{i=1}^{n} l_{bi} \qquad (5)$$

$$l_c = \sum_{i=1}^{n} l_{ci} \qquad (6)$$

where i is the individual block or blank between the intermetallic blocks, n is the total numbers of the intermetallic blocks or blanks included in the length of l. In this experimental situation, considering the feasibility and precise of the experimental data of l_b and l_c, n is selected as 20. The total bonding strength can be represented with two different kinds of interface strength as the following equation:

$$F = F_b K_b + F_c K_c \qquad (7)$$

$$F = (F_b - F_c) K_b + F_c \qquad (8)$$

where F is the total bonding strength, F_b is the bonding strength of the blank interfaces, F_c is the bonding strength of the block interfaces. There should be a linear relationship between F and K_b, the variation of F with K_b is linearly fitted as shown in Fig.7. The intercepts of the line on the axis of F are the F_b and F_c in different experimental situation, as the values of K_b are 1 and 0. F_b increases with increasing Si content.

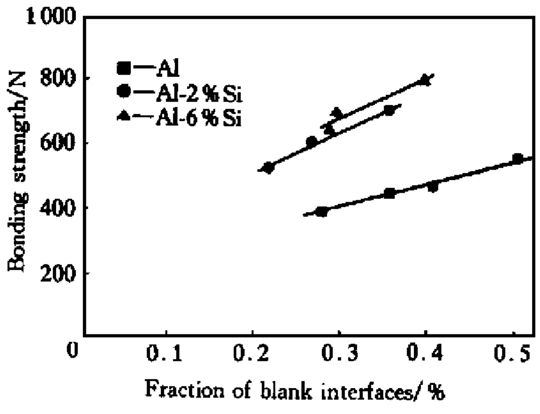

Fig.7 Bonding strength vs fraction of blank interfaces

3.4 Effect of Si content on bonding strength

The morphology and the thickness of the intermetallic layer formed during hot dip aluminizing affect the combination between the aluminized layer and the steel substrate. The thicker the intermetallic layers, the more easily the aluminized layers crack and peel during deformation. The Si content plays an important role in restraining growth of the intermetallic thickness. The reasons include: 1) the atomic saturation of the intermetallic crystal lattice for hot dipping pure aluminum is only 70 %, and lot of voids exist along the c axis of the intermetallic Fe_2Al_5. The Al atoms thus diffuse rapidly into the growth front of the Fe_2Al_5, resulting in the considerable growth of the intermetallics. When 2 % of Si is added into melt bath, the atoms of Si fill most of the voids in Fe_2Al_5, inhibiting the growth of Fe_2Al_5 in the interface region[9]; 2) In the case of an Al-6 %Si bath, Si enhances dissolving of the intermetallic phase ($Fe_xAl_ySi_z$). Therefore, the changes of Si content in melts and the hot dipping time result in the formation of the intermetallic layer with various morphology and thickness[10].

Electron microscopy and microprobe analyses revealed that there was not evident transition layer of Fe and Al in the interface region for specimens hot dipped in pure aluminum. However, 5 μm transition layer of Fe and Al formed in the interface region for those of hot dipped Al-2 %Si alloy. It may be the reason that the interfacial bonding strength increases due to the presence of Si increasing the rate of Al diffusing into steel substrate during annealing at 400 ℃.

3.5 Effect of rotation of intermetallic blocks on bonding strength

It is noted in Fig.7 that the value of bonding strength depends on the fraction of blank interfaces. The fraction of blank interfaces increases with increasing the thickness of the intermetallic layer as the dipping time is less than 2 min, and decreases beyond that, the bonding strength does either. The reason is analyzed to be the fact that during rolling, the steel substrate elongates along the direction of rolling, the intermetallics between the top coat Al layer and the steel substrate breaks into blocks owing to its brittleness, and u-shape-like blanks form in the places where the intermetallic breaks with the substrate elongating. In this process, if the intermetallic layer remains steadily parallel to the rolling surface and dose not rotate, the elongation of the specimens in the rolling direction is equal to the length of blank interfaces. The greater the elongation, the higher the fraction of blank interfaces. Therefore, with the increase of the rate of elongation δ, the K_b increases, and the equations are as following:

$$\delta = \Delta L / L \qquad (9)$$

$$K_b = \Delta L / (L + \Delta L) \qquad (10)$$

Thus the relationship between δ and K_b is

$$K_b = \delta / (1 + \delta) \qquad (11)$$

where ΔL is the elongation of the specimens, L is the length of the specimens.

Fig.8 are the photograph of rotated intermetallic blocks caused by rolling and the schematic diagram of decrease in fraction of blank interface caused by rotation. Fig.9 shows the comparison results between the measured and theoretical fraction of blank interfaces by using Eqn.(10) for hot dipped pure aluminum specimens. It is noted that two kinds of fractions of blank interface change in the same way and their values are close before 73 μm. Beyond 73 μm the curve trends to decrease. Observations of the intermetallic blocks reveal that the intermetallic blocks in thickness less than 73 μm, i.e. dipping for 0.5, 1, 2 min, do not rotate obviously. However, the intermetallic blocks of bonded specimen dipped for 4 min rotate clearly around an angle of about 30 degrees. This results in the growth of length of the intermetallic blocks at the interface, and correspondingly K_b decreases. Thus, it is necessary that the theoretical K_b from Eqn.(9) be corrected as $K_b = 1 - (1 - K_b)/\cos\theta$, where θ is the rotation angle of the intermetallic blocks. The thin gap between the corrected and measured fractions of blank interfaces reflects the principle that K_b increases with increasing the thickness of the intermetallic layer, and decreases beyond a certain value of thickness.

4 CONCLUSIONS

1) The hot-rolled bonding of hot dipped aluminum steel sheets and Al-Pb bearing alloy strips is combined through a mechanism that during rolling,

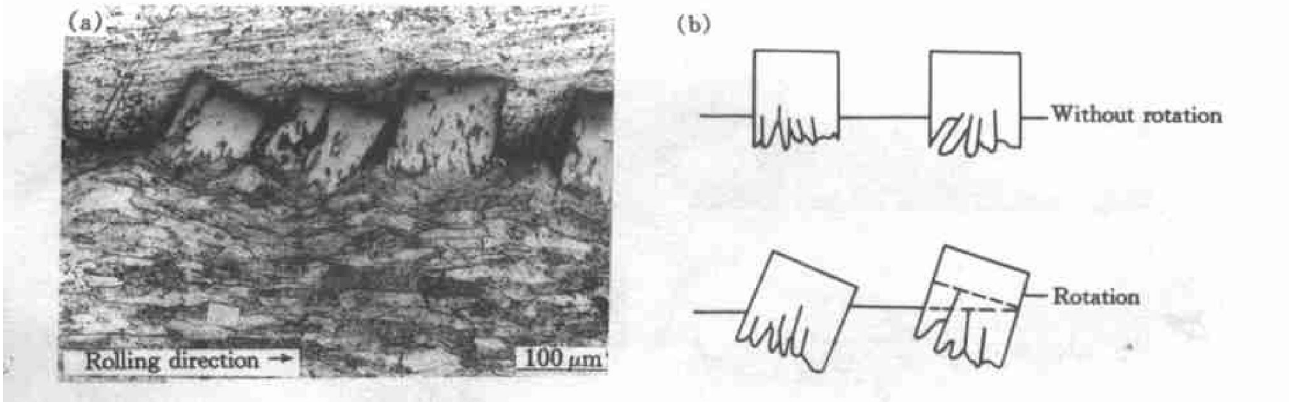

Fig.8 Decrease in fraction of blank interface caused by rotation
(a) —Photomicrograph; (b) —Schematic diagram

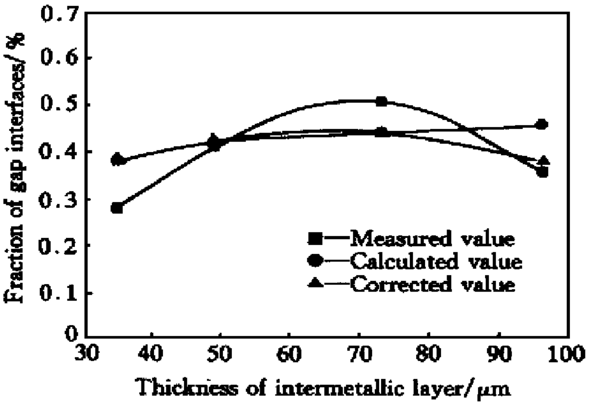

Fig.9 Measured K_b and calculated K_b

the intermetallics breaks into blocks, and between them form blanks. Thus part of Al-Pb alloy strips is bonded with Al or Al-Si top coat layer on the blocks, the rest is bonded with Al or Al-Si top coat layer on blanks of the steel substrate.

2) In the case of same melt bath, the interfacial bonding strength increases with increasing the thickness of the intermetallic layer when the dipping time is less than 2 min, and decreases with increasing the thickness of the intermetallic beyond that. The bonding strength increases with increasing the content of Si.

3) The bonding strength can be represented as $F = (F_b - F_c) K_b + F_c$, namely, there is a linear relationship between the bonding strength and the fraction of blank interfaces.

4) K_b increases with increasing the thickness of intermetallic layer until a certain thickness, then decreases with the rotation of the intermetallic blocks around the axis perpendicular to rolling direction. Therefore the theoretical K_b must be corrected as $K_b = 1 - (1 - K_b)/\cos\theta$.

[REFERENCES]

[1] Tiwari S N, Pathak J P, Malhotra S L, et al. Microstructures and mechanical properties of leaded aluminum alloy [J]. Met Tech, 1983, 10: 413.

[2] Mohan S N, Agarwala V, Rays S, et al. The effect of lead content on the wear characteristics of a stir-cast Al-Pb alloy [J]. Wear, 1990, 140: 83.

[3] Tiwari S N, Pathak J P, Malhotra S L, et al. Production of high-leaded aluminum by impeller mixing [J]. Met Tech, 1979, 6: 442.

[4] Mohan S N, Agar Wala V, Ray S, et al. Friction characteristics of stir-cast Al-Pb alloys [J]. Wear, 1992, 157: 9.

[5] Modolfo L F. Aluminum Alloys [M]. London: Butterworth, 1976. 352.

[6] SUN Da-ren, LIU Yong-bing, AN Jian, et al. Effects of cooling velocity and lead content on microstructure of cast Al-Pb alloy [J]. The Chinese Journal of Nonferrous Metals, (in Chinese), 1998, 8(suppl.1): 141.

[7] LIU Yong-bing, SUN Da-ren, AN Jian, et al. A new cast aluminum-lead bearing alloy for automobile industry [A]. WANG X J, WANG Z B eds. Proceedings of the International Conference on Advanced Automobile Materials [C]. Beijing: The Chinese Society for Metals, 1997. 355 - 358.

[8] PAN D, GAO K, YU J, et al. Cold roll bonding of bimetallic sheets and strips [J]. Materials Science and Technology, 1989, 5: 934.

[9] Eggeler G, Auer W, Kaesche H, et al. The influence of Si on the growth of the alloy layer during hop dip aluminizing [J]. J Mater Sci, 1986, 21: 3348.

[10] Elmahallawy N A, Taha M A, Shady M A, et al. Analysis of coating layer formed on steel strips during aluminising by hot dipping in Al-Si baths [J]. Mater Sci Technol, 1997, 13: 832.

(Edited by YUAN Sai-qian)