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Hot-Roll Bonding of Al-Pb Bearing Alloy Strips and Hot Dip Aluminized Steel Sheets

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In this paper, the basic bonding mechanism between two materials of practical importance is identified. One of the materials is carbon steel, which has been aluminized on its surface by immersion in molten aluminum. This step produced a Fe-Al intermetallic compound layer. The other material is an Al-Pb alloy (a bearing material). The two materials were hot roll bonded together. It was found that the Fe-Al intermetallic compound broke into discontinuous blocks during the hot rolling operation. The block of intermetallic compound remained bonded to the steel. The overall bond between the Al-Pb strip and the steel strip resulted from two different bonds. The Al-Pb strip and the Fe-Al intermetallic compound (this is called the "block bond" in this paper) and the Al-Pb strip and the bare steel surface in the area where the block separated from the steel substrate (this is called the "blank bond" in this paper).

The effects of dipping time and thickness of the intermetallic layer as well as the fractional amount of blank interfaces on the interfacial bonding strength were investigated. The total bonding strength mainly depended on that of blank interfaces and the area fraction of blank interfaces. There was a linear relationship between total bonding strength and fraction of blank interfaces. The bonding strength of blank interfaces was four times as high as that of the block interfaces. The fraction of blank interfaces increased with increasing intermetallic thickness values below 73 μm and decreased beyond 73 μm.

Keywords Al-Pb bearing alloy, blank interface, block interface, intermetallic compound

1. Introduction

Bimetallic sheets of aluminum alloys on steel have found considerable application in sliding bearings in recent years due to their outstanding advantages over other bearing materials. Among these alloys, Al-Pb alloys have attracted attention as an alternative to the widely used Al-Sn bearing alloys, since the former not only provide a better leaded film of lubricant but also are much cheaper than the latter.[1] However, the fabrication of Al-Pb alloys presents problems, because segregation exists due to the large difference in density between aluminum and lead and immiscibility exists for lead contents greater than 1.5% at temperatures above 931.5 K.[2] Unconventional attempts such as stir casting have been tried to disperse lead uniformly in aluminum alloys,[3,4] and friction characteristics of stir-cast Al-Pb alloys were reported.[4–7] Bimetallic bearings of aluminum-base alloys on a steel backing (support member) are commonly produced by cold rolling. Because of the low bonding strength between the bearing alloy (such as an Al-Sn alloy) and its steel backing, a transit layer, usually of pure aluminum, is first bonded to the steel backing; then, an aluminum-base bearing alloy is bonded to the coated steel backing. However, all existing techniques for producing bimetallic sheets of aluminum and steel by solid phase cold rolling encounter problems of low primary bonding strength; extraordinarily high reduction in material thickness (about 70%) to ensure good bonding,[8] sometimes exceeding the load capacity of conventional mills; and high work hardening of the bimetal, which restricts their further deformation. If hot-roll bonding is employed in an environment without a protective (inert) gas, oxidation on the surface of steel sheets causes it to fail to bond them tightly because of the fragile oxidation layer on the steel sheets. However, hot-roll bonding can be accomplished smoothly by using hot dip aluminized steel sheets as the material of the steel backing. Therefore, high initial bonding strength and negligible work hardening of composite plates can be achieved. In hot dip aluminizing, the base metals are coated by immersion in a molten metal bath. When low carbon steel and liquid aluminum are in contact with each other, a process of reaction diffusion takes place, resulting in the formation of intermetallic compound adjacent to the steel substrate. On withdrawing the specimen from the melt, some liquid metal sticks to the solid and solidifies according to the cooling conditions. For an initially pure aluminum melt, the alloy layer consists mainly of the intermetallic eta phase, Al_5Fe_2.[9]

At present, there is no published investigation on the mechanism of interface bonding and influence of hot dip aluminizing process on bonding strength of Al-Pb alloy strips and hot dip aluminized steel sheets by hot rolling. For these reasons, the purpose of this paper is to make a systematic analysis of the effects of dipping time, intermetallic compound layer thickness, and interface components on the bonding strength of Al-Pb alloy strips and hot dip aluminized steel sheets.

2. Experimental Details

2.1 Stir Casting and Fabrication of Al-Pb Alloy Strip

Base alloy (2.5 kg) with the chemical composition shown in Table 1 was charged into a crucible kept in a resistance-heated vertical muffle furnace. When the molten melt reached

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Table 1 The chemical composition of the base alloy, wt.%

Cu	Si	Mg	Mn	Sn	Al
1.0	4.0	0.5	0.4	1.0	Bal

973 K, the furnace was switched off and preheated baffles were pushed into the crucible. In the meantime, 0.3 kg of lead shots was added into the base alloy melt at a proper velocity and the melt was agitated at 40 rev/s with a nine-bladed flat stirrer. After stirring for 5 min, the crucible was taken out of the furnace and the turbulent melt poured into a steel mold. The elaborate casting procedure has been discussed by others.[3,4] Thus, a cylindrical ingot was obtained, then extruded into strips of 75 mm in width and 1.2 mm in thickness at 400 °C.

2.2 Preparing Hot Dip Aluminized Steel Sheets

The steel sheets with composition (wt.%) of Fe-0.09%C-0.40%Mn-0.0220%P-0.0014%S were cut into 75 × 20 × 1.5 mm strips. Prior to hot dip aluminizing, the steel sheets were pretreated through some processes such as degreasing, rinsing, rust removing, rinsing, fluxing, and drying.[10,11] To obtain various thicknesses of the intermetallic layers during hot dipping in pure aluminum bath at 700 °C; the dipping time was chosen to be 0.5, 1, 2, 3, and 4 min, respectively. The thicknesses of the intermetallic layers were measured five times at different places on the section of metallographic samples with a Nikon (Microanalysis Center of Jilin University) optical microscope.

2.3 The Hot-Roll Bonding of Al-Pb Alloy Strips and Hot Dip Aluminized Steel Sheets

The Al-Pb alloy strips were cut to 75 × 20 × 1.1 mm. The surfaces of the Al-Pb alloy strips and the hot dip aluminized steel sheets were polished with emery paper. The Al topcoat layers on the surface of steel sheets were partly removed and left with about 30 μm of thickness. Prior to hot rolling, a little part of the surface at one end of an aluminized steel sheet facing the Al-Pb alloy strip was smeared with graphite. Thus, the interface with graphite between Al-Pb alloy and aluminized steel sheets could not be rolled together tightly. One of the Al-Pb alloy strips was located in between steel sheets and heated in a furnace at 400 °C for 30 min, then immediately rolled together with a deduction of 40% to make a triplex plate. The triplex plate was then annealed at 400 °C for 30 min. After that, two u-shape-like grooves with 1.5 mm width and 0.7 mm depth were machined across both flank surfaces 20 mm away from the other end of the triplex plate, as shown in Fig. 1. The part under the grooves was pressed tightly between a pair of steel jaws, as shown in Fig. 1(left) and the interface with graphite was torn to the place where the u-shape-like grooves were, but could not reach beyond them because of the state of pressing under the grooves. Finally, two torn parts were bent outwardly around an angle of nearly 90°; the specimen took the shape as sketched in Fig. 1(right). To measure the bonding strength, one end of the specimen was held tightly while the other end was loaded. The weights were added step by step, and the minimum step

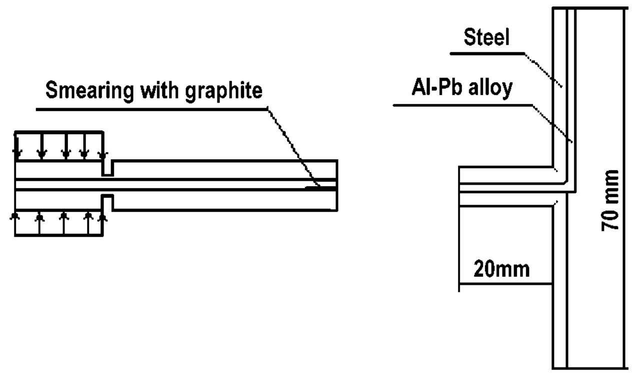


Fig. 1 Schematic diagram of bonded specimen

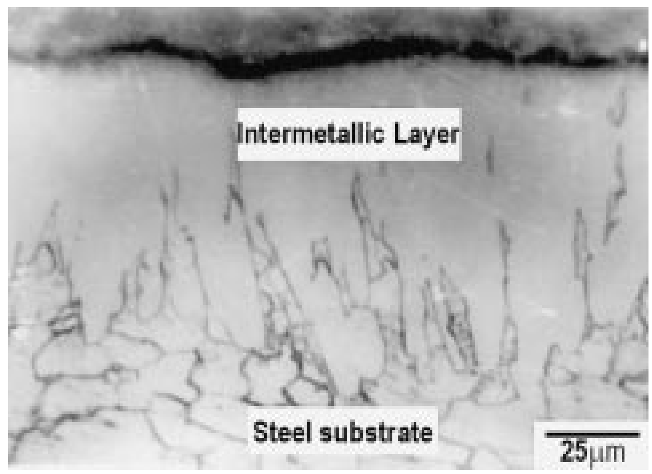


Fig. 2 Photomicrograph of aluminized layer on steel substrate: 700 °C for 2 min

value of weights was 4.9 N, until the unsteady fracture occurred along the bonded interface. Then, the average weight value taken from three bonded specimens was used as a measure of the bonding strength of the interface. This method is similar in principle to one used by others[8] but is much closer to the rolled state.

3. Results and Discussion

3.1 Morphology of the Hot Dip Aluminized Layer

After hot dip aluminizing at 700 °C for 0.5, 1, 2, 3, and 4 min, the hot dip aluminized layers were observed as shown in Fig. 2. The cross section of the aluminized steel sheets revealed the appearance of an intermetallic layer covered with an aluminum topcoat layer; both formed on the steel substrate. The outer layer is composed of pure aluminum; its thickness ranges from 43 to 87 μm. Below it, the tongue-shaped layer is mainly composed of Fe_2Al_5 and the intermetallic phase previously observed.[12–16]

The thickness of the intermetallic compound layer was measured, and the parabolic relationship between thickness and

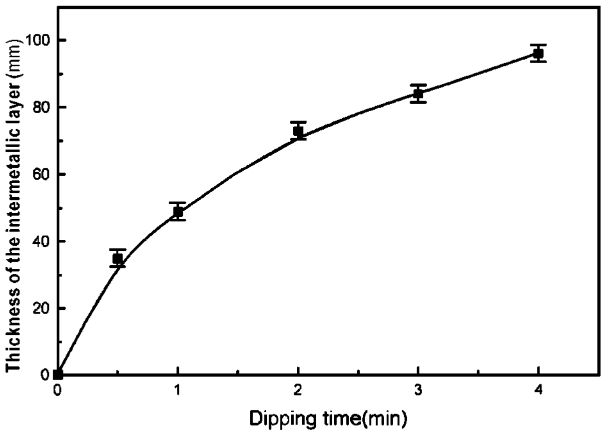


Fig. 3 The variation in the thickness of the intermetallic layer with dipping time

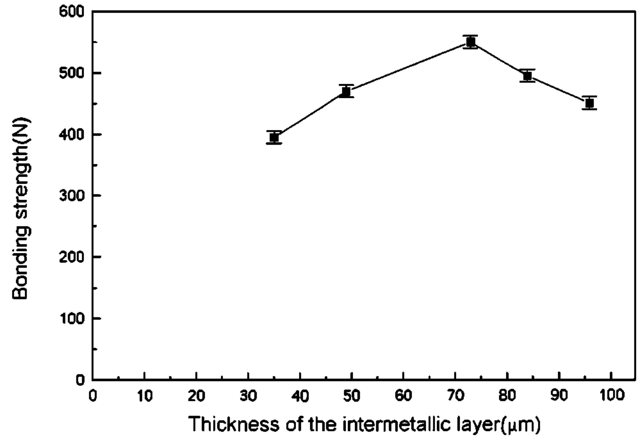


Fig. 5 The variation in bonding strength with thickness of the intermetallic layer

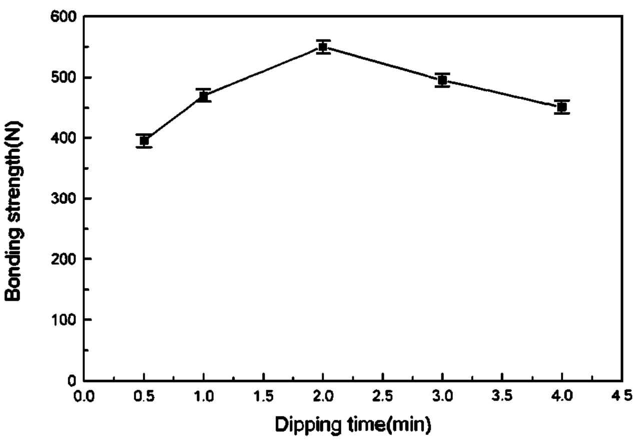


Fig. 4 The variation in bonding strength with dipping time

dipping time is shown in Fig. 3, similar to the findings of previous works.[10,11] The thickness of intermetallic layers increases with dipping time.

3.2 Bonding Strength

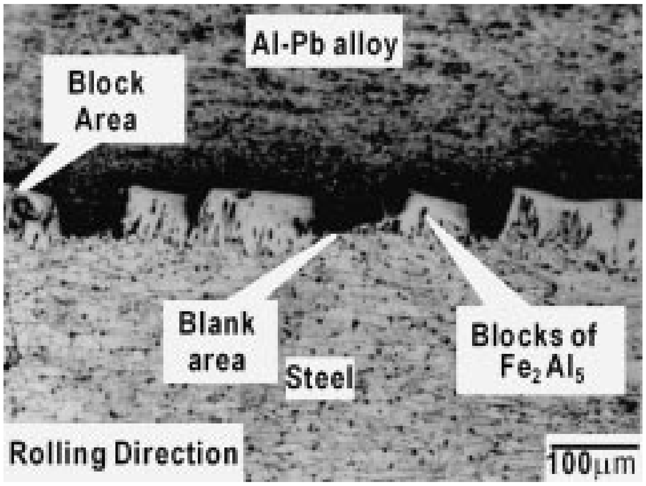
The variation in bonding strength with dipping time is shown in Fig. 4. It is noted that the bonding strength increases with dipping time before 2 min, and decreases beyond that. It was observed that the dipping time had no effect on the intermetallic structure and composition but only on its thickness in these experimental situations. Thus, the relationship between bonding strength and intermetallic thickness is more direct than that between bonding strength and dipping time. Therefore, the variation in bonding strength with the intermetallic thickness is plotted in Fig. 5. Below 73 μm, the bonding strength increases with intermetallic thickness; it then decreases beyond 73 μm.

3.3 Bonding Mechanism

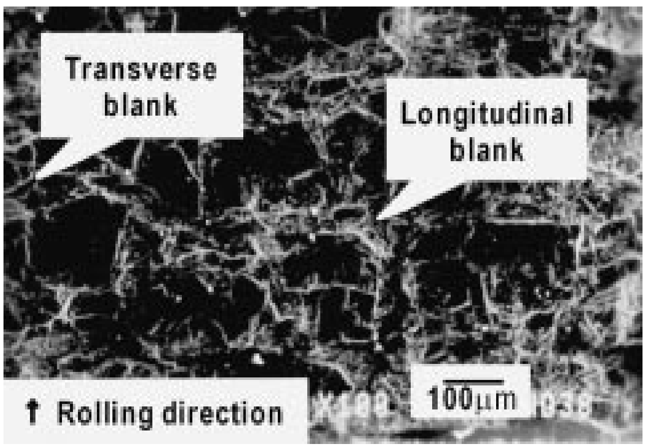
Figure 6(a) is the longitudinal section photomicrograph of bonded specimens of Al-Pb alloy-hot dipped aluminum steel sheet. It clearly shows that, in the direction of rolling, the intermetallic compound layer breaks into blocks, and blanks form between them. Figure 6(b) and (c) are the photographs (scanning electron microscopy) of the fractured interface on the steel side. The wider blanks in the direction of rolling are parallel to each other across the surface of steel substrate. And there are also narrower blanks perpendicular to the direction of rolling. The formation of these blanks is due to the fact that the steel substrate elongated in the direction of rolling, but the intermetallic layer could not elongate with the steel substrate due to its brittleness and it broke into small blocks. The same practice also occurred for those blanks perpendicular to the rolling direction. In these experimental situations, the length of longitudinal blanks was much greater than that of transverse blanks, as shown in Fig. 6(b). Therefore, in the rolling process, both the Al-Pb alloy strips and aluminum top coat layer adjacent to the intermetallic layer elongated in the direction of rolling and were squeezed into blanks to fill them. Thus, two different bonding processes took place, Al-Pb alloy was bonded to aluminum layer both above the intermetallic blocks (block area) and at the bottom of blanks (blank area). Meanwhile, the aluminum topcoat layer was bonded to both intermetallic blocks in the block area and to steel substrate in the blank area. Therefore, two different sets of bonded interfaces were produced, *i.e.*, Al-Pb/Al interface and Al/(compound and steel) interface. The analysis of lead mapping by electron probe microanalysis 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 top coat 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 latter. The fracture occurs along the weaker interface, *i.e.*, Al/(compound and steel) interface. Thus, the fractured interface is composed of block interfaces and blank interfaces.

3.4 The Effects of Interface Components on Bonding Strength

The positions of the interfaces mentioned above are sketched in Fig. 7. Obviously, the total bonding strength depends on the two different components of fractured interfaces, *i.e.*, blank



(**a**)



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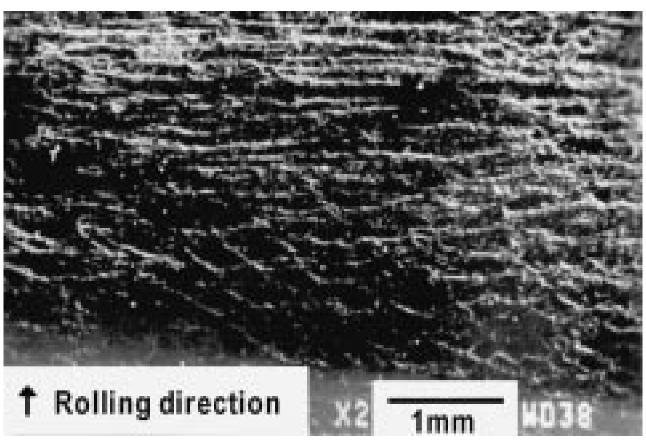

(**c**)

Fig. 6 Microstructure of bonded interface in the case of dipping for 2 min. (**a**) Longitudinal section photograph of Al-Pb alloy-hot dipped Al steel sheet (optical microscopy). (**b**) Fractured interface on hot dipped Al steel side (scanning electron microscopy). (**c**) Parallel blanks across fractured interface on hot dipped Al steel side (scanning electron microscopy)

interfacial bonding strength and block interfacial strength. The stronger one will control the total strength. To evaluate their

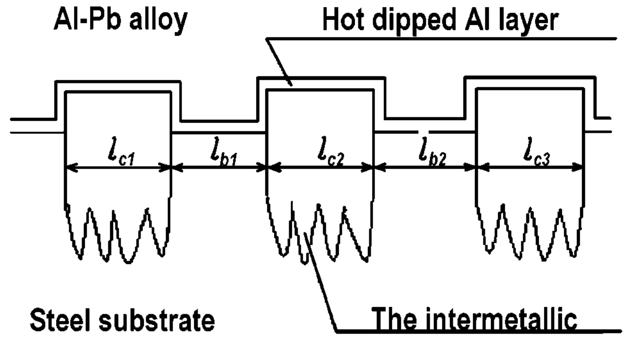

Fig. 7 Schematic diagram showing position of Al-Pb/Al top coat layer interface and Al top coat layer/intermetallic block and steel substrate interface after hot rolling

respective effects, the total bonding strength was represented with two different kinds of interface strengths as the following equation:

$$F = F_b K_b + F_c K_c \tag{Eq 1}$$

where F is the total bonding strength, F_b is the bonding strength of the blank interfaces between the intermetallic blocks, F_c is the bonding strength of block interfaces on the top of the intermetallic blocks, K_b is the area fraction of the blank interfaces, and K_c is the area fraction of block interfaces.

In order to determine K_b and K_c, the transverse blanks are neglected. The following relationships are used:

$$K_b = l_b/l \tag{Eq 2}$$

$$K_c = l_c/l \tag{Eq 3}$$

$$K_b + K_c = 1 \tag{Eq 4}$$

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

$$l = l_\mathrm{b} + l_\mathrm{c} \tag{Eq 5}$$

$$l_b = \sum_{i=1}^{n} l_{bi} \tag{Eq 6}$$

$$l_c = \sum_{i=1}^{n} l_{ci} \tag{Eq 7}$$

where i is the individual intermetallic block or blank between the intermetallic blocks, as shown in Fig. 7; and n is the total number of the intermetallic blocks or blanks included in the length of l. In this experimental situation, considering feasibility and accuracy of the experimental data of l_b and l_c, n is selected to be 20.

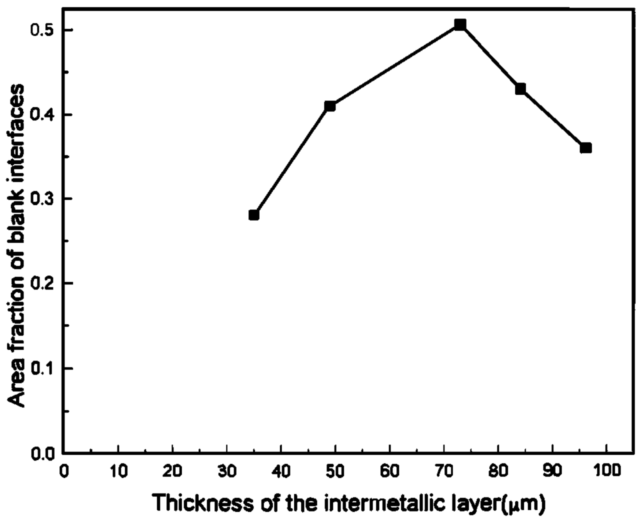

Fig. 8 The variation in area fraction of blank interface with the thickness of the intermetallic layer

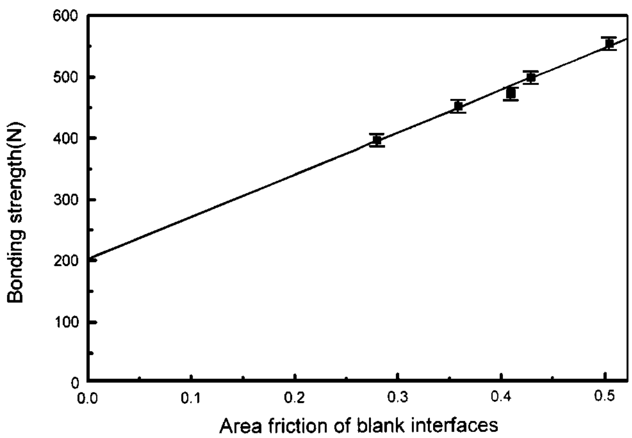

Fig. 9 The liner relationship between bonding strength and area fraction of blank interfaces

Figure 8 shows that the area fraction of blank interfaces increases with the intermetallic layer thickness below 73 μm, but decreases beyond that value. The total bonding strength can also be represented as the following equation:

$$F = (F_b - F_c)K_b + F_c \quad \text{(Eq 8)}$$

There should be a linear relationship between F and K_b, and F should increase with an increase in K_b. The variation in bonding strength with the fraction of blank interfaces is shown in Fig. 9. The data points fit a linear relation. The values of F_b and F_c can be obtained from the ordinate in Fig. 9, as the values of K_b are 0 and 1. The value of K_b being 0 or 1 means that the bonded interface entirely consists of block interfaces or blank interfaces. The values of F_b and F_c are found to be equal to 881.0 and 202.2 N, respectively, indicating that bonding strength of blank interfaces is 4 times as high as that of block interfaces on the top of the intermetallic. So, the total bonding strength mainly depends on the bonding strength of blank interfaces and the fraction of blank interfaces.

4. Conclusions

The study of interfacial bonding strength of Al-Pb bearing alloy and hot dip aluminized steel sheets by hot rolling leads to the following conclusions.

- Bonding Al-Pb alloy strips with hot dip aluminized steel sheets could be carried out smoothly by using hot roll, and they were bonded together in a mechanism of blank interface bonding and block interface bonding.
- In the current rolling operation, bonding strength increased with the thickness of intermetallic layer below 73 μm; beyond that, it decreased. It agrees with the change in the area fraction of blank interfaces.
- The total bonding strength mainly depended on the blank interface bonding strength and the area fraction of blank interfaces, and the bonding strength of blank interfaces was 4 times as high as that of block interfaces. There was a linear relationship between total bonding strength and the area fraction of blank interfaces in these experimental situations.

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References

1. Y.S. Avraamov, V.P. Filonenko, A.P. Gruzdov, and A.D. Shlyapin: *Mater. Sci. Heat Treatment,* 1984, vol. 26 (4), pp. 543-46.
2. L.F. Mondolfo: *Aluminum Alloys, Structure and Proprieties,* Butterworth and Co., London, 1976, pp. 352-65.
3. S. Mohan, V. Agarwala, and S. Ray: *Z. Metallkd.,* 1989, vol. 80, pp. 904-08.
4. S. Mohan, V. Agarwala, and S. Ray: *Wear,* 1990, vol. 140, pp. 83-92.
5. J. Pathak, S.N. Tiwari, and S.L. Malhotra: *Wear,* 1986, vol. 112, pp. 341-53.
6. S. Mohan, V. Agarwala, and S. Ray: *Wear,* 1992, vol. 157, pp. 9-17.
7. A. Sharma and T.V. Rajan: *Wear,* 1996, vol. 197, pp. 105-14.
8. D. Pan, K. Gao, and J. Yu: *Mater. Sci. Technol.,* 1989, vol. 5 (9), pp. 934-39.
9. G. Eggeler, W. Auer, and H. Kaesche: *Z. Metallkd.,* 1986, vol. 77, pp. 239-44.
10. S.G. Denner and R.D. Jones: *Met. Technol.,* 1977, vol. 4, pp. 161-74.
11. N.A. EI-Mahallawy, M.A. Shady, and A.R. EI-Sissi: *Mater. Sci. Technol.,* 1997, vol. 13 (10), pp. 832-40.
12. S.C. Kwon and J.Y. Lee: *Met. Technol.,* 1981, vol. 8, pp. 373-75.
13. S. Baumgartl, L. Hachtel, and G.-K. Werners: *Prakt. Metallogr.,* 1994, vol. 31, pp. 162-78.
14. G. Langenscheid and G. Klein: *Parkt. Metallogr.,* 1977, vol. 14, pp. 251-62.
15. M. Hansen and K. Anderko: *Constitution of Binary Alloys,* McGraw-Hill, New York, NY, 1958, pp. 90-95.
16. G. Eggeler, H. Vogel, J. Friedrich, and H. Kaesche: *Prakt. Metallogr.,* 1985, vol. 22, pp. 163-70.