

Interface of solid steel and liquid aluminum under nonequilibrium diffusion^①

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Abstract: The nonequilibrium diffusion of liquid aluminum atoms in cross direction in the innerpart of the solid steel base has been realized by using methods such as roughening steel plate surface, immersing flux on steel plate surface and short-time diffusion, and the interface of solid steel and liquid aluminum under nonequilibrium diffusion in cross direction was formed by using rapid solidification. The interfacial structure was studied by means of electron probe microanalysis. The results showed that the interfacial structure of solid steel and liquid aluminum under nonequilibrium diffusion in cross direction is quite different from that of solid steel and liquid aluminum under conventional diffusion, that is, the interface of solid steel and liquid aluminum under nonequilibrium diffusion in cross direction is made up of groups of $\text{Al}_{13}\text{Fe}_4$ teeth (which grew from the contact surface to steel base inner) at the bulges of steel plate surface and Fe-Al solid solution (whose Al content is less than 3.5%) at the concaves of steel plate surface between the groups of $\text{Al}_{13}\text{Fe}_4$ teeth.

Key words: nonequilibrium diffusion; cross direction; rapid solidification; interfacial structure **Document code:** A

1 INTRODUCTION

The current products of solid steel and liquid aluminum under conventional diffusion mainly include hot-dip aluminizing steel plate^[1~3] and steel-aluminum solid to liquid bonding plate^[4~6]. The diffusion of aluminum atoms in the innerpart of solid steel base is rather sufficient not only in lengthwise direction but also in cross direction, so it reaches equilibrium in cross direction. The typical interfacial structure of these products is Al, FeAl_3 , Fe_2Al_5 and Fe in turn from aluminum to steel base^[7]. The Fe-Al brittle compounds FeAl_3 and Fe_2Al_5 form a middle brittle layer whose thickness is generally about 40 μm . When other elements such as Si are added in aluminum liquid, the thickness of the middle brittle layer can reduce to about 15 μm ^[8,9]. But no matter how thin the middle brittle layer is, the Fe-Al brittle compounds always form a continuous layer because of the equilibrium diffusion of aluminum atoms in cross direction. However, the continuous layer structure of FeAl_3 and Fe_2Al_5 can embrittle the interface of product, so the interfacial mechanical properties are relatively lower. Therefore we must try to destroy the continuous middle brittle layer at the interface in order to remove the embrittlement of the interface.

It is well known that the formation of Fe-Al compound is the result of the diffusion of aluminum

atoms in the innerpart of steel base and the reaction with Fe atoms. If the diffusion of aluminum atoms is nonequilibrium in cross direction in the innerpart of steel base, the distribution of Fe-Al compound in cross direction will be different at the interface, that is, the continuous middle brittle layer will be destroyed, and the embrittlement of the interface will be avoided. This is the basic idea of nonequilibrium diffusion method.

For the first time, the nonequilibrium diffusion of liquid aluminum atoms in cross direction in the innerpart of solid steel base has been realized by using methods such as roughening steel plate surface, immersing flux on steel plate surface and short-time diffusion, and the interface of solid steel and liquid aluminum under nonequilibrium diffusion in cross direction was formed by using rapid solidification. The interfacial structure was determined by means of electron probe microanalysis.

2 EXPERIMENTAL

The experimental materials were 1.2 mm-thick 08Al steel plate and industrially pure aluminum (99.99%). The experimental procedures were as follows. Welded the steel plate to the bottom of the cooling box for rapid solidification, as shown in Fig. 1. Defatted, descaled and roughened the surface of

① **Foundation item:** Project 715 - 009 - 060 supported by the Advanced Technology Committee of China

Received date: Feb. 23, 1999; **accepted date:** Jul. 19, 1999

the steel plate in order to get fresh surface to contact with aluminum liquid. Immersed the steel plate surface in flux (K_2ZrF_6) aqueous solution for 1 min in order to form about $10\text{ }\mu\text{m}$ -thick flux layer on the surface to prevent the fresh surface of the steel plate from oxidizing. The concentration of the flux aqueous solution was 7 %. The flux aqueous solution must be heated to $90\text{ }^\circ\text{C}$ so as to increase the density of the flux layer. Stoved the steel plate at the bottom of cooling box for 1 min at $200\text{ }^\circ\text{C}$ in order to remove the water in the flux layer. Fixed the cooling box onto the supporting frame (the experimental apparatus was shown in Fig.2). Dropped the cooling box into the aluminum liquid to realize nonequilibrium diffusion of aluminum atoms in cross direction in the innerpart of solid steel base. After 4 s, pumped the cooling water into the cooling box immediately to realize rapid solidification from the steel side (the cooling speed was about $2000\text{ }^\circ\text{C/s}$) in order to obtain the interface of solid steel and liquid aluminum under nonequilibrium

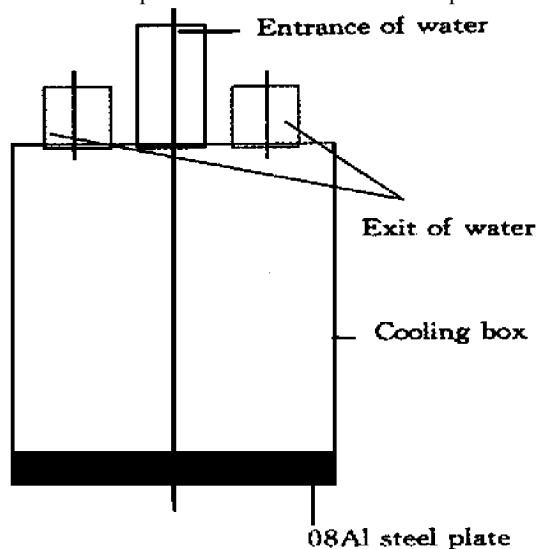


Fig.1 Cooling box sketch

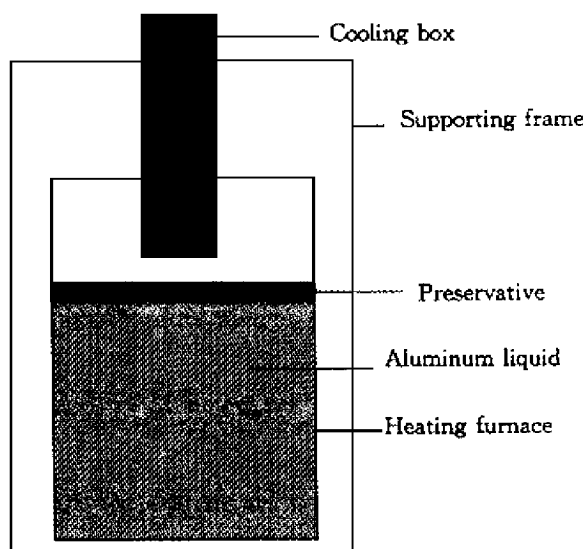


Fig.2 Experimental apparatus sketch

diffusion in cross direction, and raised the cooling box at a speed of 10 m/s at the same time in order to obtain about 4 mm -thick solid aluminum layer on steel plate. The industrially pure aluminum liquid was refined and its temperature was $800\text{ }^\circ\text{C}$. In order to prevent liquid aluminum from oxidizing at high temperatures, a layer of preservative was used to cover the surface of the aluminum liquid in the heating furnace. Disboarded the cooling box from the supporting frame and cut the steel-aluminum plate from the cooling box on a lath. Cut the steel-aluminum plate into blocks of $10\text{ mm} \times 10\text{ mm} \times 5.2\text{ mm}$ by linear cutting method. Carefully ground, polished, eroded, cleaned and dried the side of the block to make the sample for electron probe microanalysis. The volume composition of the corrosive agent used was 0.5 % HF, 1.5 % HCl, 2.5 % HNO_3 and 95.5 % H_2O . At last, conducted electron probe microanalysis to observe interfacial structure and analyze its composition.

3 RESULTS AND DISCUSSION

Fig.3 shows the SEI micrograph of the interface of steel-aluminum plate under nonequilibrium diffusion in cross direction. The left dark side is aluminum region; the right white side is 08Al steel base. The juncture of aluminum and steel base is the interface. It can be seen that the interface is made up of regions 1, 2 and 3. Regions 1 and 3 which distribute at the bulges of solid steel base are made up of the teeth which grew from the contact surface to the steel base inner. Fig.4 shows the AlK_α line scan of region 1. Fig.5 shows the FeK_α line scan of region 1. From these two figures, it can be seen that the composition of the teeth is basically changeless. The results of multi-point composition quantitative analysis of the teeth are 39 % Fe, 61 % Al. According to the mass fractions, the molecular formula of the tooth phase is $\text{Al}_{13}\text{Fe}_4$. So regions 1 and 3 are groups of $\text{Al}_{13}\text{Fe}_4$ teeth whose maximum length is about $10\text{ }\mu\text{m}$. Region 2 distributes at the concave of solid steel base. The results of multi-point composition quantitative analysis of region 2 shows that region 2 is Fe-Al solid solution whose Al content is less than 3.5 %. Therefore, it can be said that there is no continuous middle brittle layer at the interface of steel-aluminum plate under nonequilibrium diffusion. Instead, the interface is made up of groups of $\text{Al}_{13}\text{Fe}_4$ teeth at the bulges of steel base and Fe-Al solid solution at the concaves of steel base between the groups of $\text{Al}_{13}\text{Fe}_4$ teeth.

When aluminum liquid contact with the solid steel plate surface, the bonding behaviors such as wetting, spreading, adsorption, diffusion and reaction would happen^[10]. Because the steel plate surface was roughened, it was scraggy, and this led to the result that the thickness of the flux layer on the steel plate surface was quite different. At the bulge of the

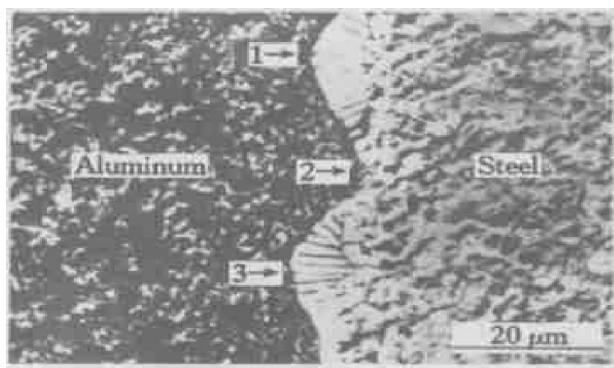
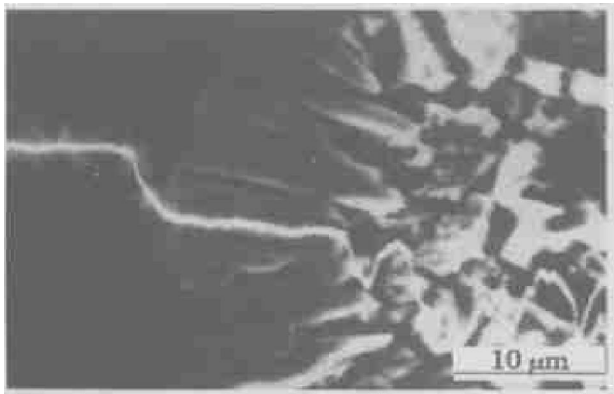


Fig.3 Interface

Fig.4 Al K_{α} line scanFig.5 Fe K_{α} line scan

steel plate surface, the thickness of the flux layer h was smaller, while at the concave of the steel plate surface, the thickness of the flux layer H was larger, as shown in Fig.6. When solid steel plate contacted with aluminum liquid, the flux on the steel plate surface began to melt and decompose. At the bulges of steel plate surface, because the thinner flux layer was firstly removed, aluminum liquid contacted with the solid steel plate surface primarily, and the bonding behaviors such as wetting, spreading, adsorption, diffusion and reaction happened firstly. It is well known that the diffusion of aluminum atoms and the transmitting of energy into the solid steel base are perpendicular to the tangent of the steel plate surface. At the bulges of steel plate surface, the direction of aluminum diffusion and energy transmitting was pointed to the curvature center of solid steel plate

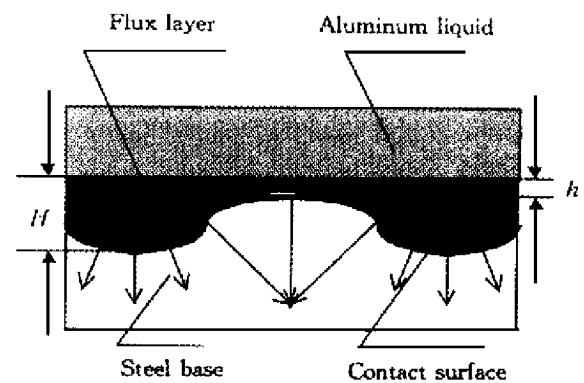


Fig.6 Contact interface sketch

surface, and thus the temperature and the concentration of aluminum in the steel base at the bulges of steel plate surface were higher than those of smooth surface. Therefore, the teeth at the bulges of steel plate surface contain more aluminum and point to the curvature center of steel plate surface, as shown in Fig.3. However, at the concave of steel plate surface, the thicker flux layer was finally removed, the liquid aluminum contacted with the solid steel plate surface secondly, some of its heat energy had transmitted into the steel base from the bulges of the steel plate surface, the temperature of this part of aluminum was relatively lower, and the direction of aluminum atom's diffusion and energy transmitting was divergent, therefore the temperature and the concentration of aluminum atoms in the steel base at the concave of steel plate surface were much lower than those of smooth surface. So at the concave of steel plate surface, only Fe-Al solid solution could form. In addition, the total time of diffusion was only 4 s which was so short that aluminum atoms and energy in steel base had not enough time to conduct cross diffusion and transmitting. Therefore, roughening steel plate surface, immersing flux at steel plate surface and short-time diffusion resulted in nonequilibrium diffusion of aluminum atoms in cross direction in the innerpart of steel base, and formed the interfacial structure with groups of $Al_{13}Fe_4$ teeth at the bulges of steel base and Fe-Al solid solution at the concaves of steel base. The rapid solidification avoided diffusion of aluminum atoms in cross direction in the innerpart of steel base during natural cooling in the air, and kept interfacial structure form under nonequilibrium diffusion directly. So the interfacial structure of solid steel and liquid aluminum under nonequilibrium diffusion in cross direction was quite a new one which increases the interfacial shear strength of steel-aluminum bonding plate from about 60 MPa to about 70 MPa.

4 CONCLUSIONS

In nonequilibrium diffusion experiment of solid

steel and liquid aluminum, methods such as roughening solid steel plate surface, immersing flux on solid steel plate surface and short-time diffusion could result in nonequilibrium diffusion of aluminum atoms in cross direction in the innerpart of steel base successfully, and rapid solidification could keep the interfacial structure of solid steel and liquid aluminum under nonequilibrium diffusion in cross direction directly. So there was no continuous middle brittle layer (which formed in conventional diffusion) at the interface of solid steel and liquid aluminum under nonequilibrium diffusion. Instead, the interface of solid steel and liquid aluminum under nonequilibrium diffusion was made up of groups of $\text{Al}_{13}\text{Fe}_4$ teeth (which grew from the contact surface to steel base inner) at the bulges of solid steel plate surface and Fe-Al solid solution (whose Al content was less than 3.5%) at the concaves of solid steel plate surface between the groups of $\text{Al}_{13}\text{Fe}_4$ teeth.

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(Edited by PENG Chao-qun)