Interfacial structure of steel–aluminum bonding plate under non-equilibrium rapid solidification

Peng Zhang\textsuperscript{a,\*}, Yunhui Du\textsuperscript{a}, Xueping Ren\textsuperscript{a}, Hanwu Liu\textsuperscript{b}, Jianzhong Cui\textsuperscript{b}

\textsuperscript{a}Department of Mechanical Engineering, Tsinghua University, Beijing 100084, People’s Republic of China
\textsuperscript{b}Department of Metal Forming, Northeastern University, Shenyang 110006, People’s Republic of China

Abstract

A steel–aluminum solid–liquid bonding plate is prepared using a non-equilibrium rapid solidification method (including four kinds of processes such as roughening the steel plate surface, immersing in flux at the steel plate surface, short-time bonding and rapid solidification). The interfacial structure of the bonding plate is investigated by means of electron probe microanalysis and X-ray diffraction. The results show that the interfacial structure of the bonding plate under non-equilibrium rapid solidification is quite different from that of the bonding plate in conventional steel–aluminum solid–liquid bonding, i.e. the interface of the bonding plate under non-equilibrium rapid solidification is made up of an aluminum-rich region (in the form of a group of Fe\textsubscript{2}Al\textsubscript{13} teeth that grow from the contact surface to the steel side) at the bulge of steel plate surface and an aluminum-poor region (in the form of Fe–Al solid solution of which the Al content is less than 3.5 wt%) at the concave surface of the steel plate alternately. © 2001 Published by Elsevier Science Ltd.

Keywords: Steel–aluminum solid–liquid bonding; Non-equilibrium rapid solidification; Interfacial structure

1. Introduction

At present, the main steel–aluminum solid–liquid products include hot-dip aluminizing steel plate [1] and steel–aluminum solid–liquid bonding plate [2]. The typical interfacial structure of these products consists of Al, Fe\textsubscript{2}Al\textsubscript{3}, Fe\textsubscript{2}Al\textsubscript{4} and Fe in series from the aluminum to the steel substrate [3]. The brittle compounds Fe\textsubscript{2}Al\textsubscript{3} and Fe\textsubscript{2}Al\textsubscript{4} from an intermediate brittle layer with a thickness generally of about 40 \textmu m. When another element such as Si is added to the aluminum liquid, the thickness of the intermediate brittle layer can reduce to about 15 \textmu m [4]. However, no matter how thin the brittle layer is, the Fe–Al brittle compounds always form a continuous layer. The continuous layer structure of Fe\textsubscript{2}Al\textsubscript{3} and Fe\textsubscript{2}Al\textsubscript{4} can embrittle the interface of the product, so for a steel–aluminum solid–liquid bonding plate the interfacial shear strength is relatively low. Therefore, if one wants to obtain products of excellent interfacial property, destroying the continuous brittle layer at the interface should be the first consideration.

It is well known that the formation of Fe–Al compound is the result of diffusion of aluminum atoms to the steel substrate and reaction with Fe atoms. If the diffusion of aluminum atoms is non-equilibrium in the steel substrate, especially in the cross direction, the distribution of Fe–Al compound will be different at the interface, the formation of the continuous intermediate brittle layer can be suppressed, and the embrittlement of the interface will be removed. This is the basic idea of non-equilibrium rapid solidification method.

In this work, steel–aluminum solid–liquid bonding is conducted using methods such as roughening the steel plate surface, immersing in flux at the steel plate surface, short-time bonding and rapid solidification in order to promote the non-equilibrium diffusion of aluminum atoms in the steel substrate. The interfacial structure of the steel–aluminum solid–liquid bonding plate under non-equilibrium rapid solidification is determined by means of electron probe microanalysis and X-ray diffraction.

2. Experimental

2.1. Non-equilibrium rapid solidification experiment

The materials used in the experiment are 1.2 mm thick 08Al steel plate and pure aluminum (99.99%). The experimental procedure is as follows. (1) Weld the steel plate to the bottom of the cooling box for rapid solidification (as shown in Fig. 1). (2) Degrease, descale, and roughen the
surface of the steel plate in order to provide a fresh surface to contact the aluminum liquid. (3) Immerse the steel plate surface in flux (K$_2$ZrF$_6$) aqueous solution for 1 min in order to form a flux layer of about 10 μm thickness on the surface to protect the fresh surface of the steel plate from oxidation. The flux concentration of the aqueous solution is 7 wt%. The flux aqueous solution must be heated to 90°C so as to increase the density of the flux layer. (4) Srove the steel plate at the bottom of cooling box for 1 min at 200°C in order to remove the water in the flux layer. (5) Fix the cooling box onto the bonding frame (the apparatus for bonding experiments is shown in Fig. 2). (6) Drop the cooling box into the aluminum liquid and conduct steel–aluminum solid–liquid bonding. After 4 s, pump cooling water into the cooling box immediately in order to cool the bonding plate from the steel side rapidly (the cooling rate is about 2000°C/s), and raise the cooling box simultaneously at a speed of 10 m/s in order to obtain a steel–aluminum solid–liquid bonding plate with an approx. 4 mm thick solid aluminum layer. The pure aluminum liquid is degassed and its temperature is 800°C. In order to prevent aluminum from oxidation at high temperature, a layer of preservative is applied to the surface of the aluminum liquid in the heating furnace. (7) Dismantle the cooling box from the bonding frame and cut the bonding plate from the cooling box on a lathe.

2.2. Electron probe microanalysis and X-ray diffraction experiments

Cut up the steel–aluminum solid–liquid bonding plate into blocks of 10 × 10 × 5.2 mm$^3$ by linear cutting methods. Carefully grind, polish, etch, clean and dry the side of the block to make the sample for electron probe microanalysis. The etching reagent is 0.5% HF, 1.5% HCl, 2.5% HNO$_3$ and 95.5% H$_2$O. After electron probe microanalysis, shear the sample at the interface and conduct an X-ray diffraction experiment on the shearing surface in order to verify the composition of the interface further.

3. Results and discussion

3.1. Experimental results

Fig. 3 is the electron probe micrograph of the interface of steel–aluminum solid–liquid bonding plate under non-equilibrium rapid solidification. The dark left side is the pure aluminum region. The right white side is 08Al steel substrate. The juncture of aluminum and steel substrate is the interface of the bonding plate. It can be seen that the interface is made up of regions 1, 2 and 3. Regions 1 and 3 (distribute at the bulges of the steel substrate) are made up of the teeth which grow from the contact surface to the steel substrate. Figs. 4 and 5 are an Al and Fe line profile of
region 1, respectively. From these two figures, it can be seen that the composition of the tooth is basically without change. The results of multi-point composition quantitative analysis of the tooth are 39 wt% (Fe), 61 wt% (Al). Thus the tooth is Fe$_2$Al$_3$. Therefore, regions 1 and 3 are groups of Fe$_2$Al$_3$ teeth having a maximum length of about 10 μm. Region 2 is distributed at the concave part of the steel substrate. The results of multi-point composition quantitative analysis of region 2 show that region 2 is Fe–Al solid solution with an Al content of less than 3.5 wt%. Fig. 6 is an X-ray diffraction pattern from the shearing surface of the aluminum. It can be seen that there are three kinds of matter, i.e. Al, Fe$_2$Al$_3$, and Fe (which forms Fe–Al solid solution together with Al) at the shearing surface, and this verifies the results of electron probe microanalysis further. Therefore, it can be concluded that there is no continuous intermediate brittle layer at the interface of a steel–aluminum solid–liquid bonding plate under non-equilibrium rapid solidification, and that the interface is made up of groups of Fe$_2$Al$_3$ teeth at the bulges of the steel substrate and Fe–Al solid solution at the concave parts of the steel substrate, respectively. This type of interfacial structure removes the embrittlement of the interface and increases the interfacial shear strength of steel–aluminum solid–liquid bonding plate from about 60 to about 70 MPa (this is the result of further mechanical property experiments).

3.2. Discussion

When aluminum liquid contacts the steel plate surface, bonding behavior such as wetting, spreading, adsorbing, diffusing and reacting take place [5]. Because the steel plate surface is roughened and scraggy, this results in the different thickness of the flux layer on the steel plate surface. At the bulge of the steel plate surface, the thickness of the flux layer $h$ is smaller, and at the concave part of the steel plate surface, the thickness of the flux layer $H$ is larger (as shown in Fig. 7). When the steel plate contacts the aluminum liquid, the flux on the steel plate surface begins to melt and decompose. At the bulge of the steel plate surface, because the thinner flux layer is firstly removed, aluminum liquid contacts the steel plate surface and the bonding starts firstly. It is well known that the diffusion of aluminum and the transmission of energy into the steel substrate are perpendicular to the tangent of the steel plate surface. Thus at the bulge of the steel plate surface, the direction of aluminum diffusion and energy transmission is pointed towards the curvature center of the steel plate surface, and therefore the temperature and the aluminum concentration in the steel substrate at the bulge of the steel plate surface are higher and bigger than those at the straight surface. Thus the teeth at the bulges of the steel plate surface contain more aluminum and their shapes point to the curvature center of the steel plate surface (as shown in Fig. 3). However, at the concave part of the steel plate surface, the thicker flux layer is last to be removed, then the aluminum can contact the steel plate surface. Some of its thermal energy is transmitted into the steel substrate from the bulge of the steel plate surface, the temperature of this part of aluminum is relatively lower, and the direction of aluminum diffusion and energy transmission is divergent, therefore the temperature and the aluminum concentration in the steel substrate at the concave part of the steel plate surface are much lower and smaller than those at the straight surface. Thus at the concave part of the steel plate surface only Fe–Al solid solution can form. In addition, the whole time of bonding is only 4s which is so short that aluminum atoms and energy in the steel substrate have not enough time to conduct cross diffusion and transmission, therefore the interfacial structure which exists.
in the process of bonding is maintained by rapid solidification directly.

4. Conclusion

In non-equilibrium rapid solidification bonding, methods such as roughening the steel plate surface, immersing in flux at the steel plate surface and, short-time bonding, successfully result in non-equilibrium diffusion of aluminum atoms into the steel substrate, and rapid solidification directly maintains the interfacial structure which exists in the process of bonding. Accordingly, there is no continuous intermediate compound layer, which usually forms in conventional steel–aluminum solid–liquid bonding. Instead, the interface of a steel–aluminum solid–liquid bonding plate under non-equilibrium rapid solidification is made up of groups of Fe₄Al₁₃ teeth (growing from the contact surface to the steel substrate) at the bulges of the steel plate surface, and Fe–Al solid solution (whose Al content is less than 3.5 wt%) at the concave parts of the steel plate surface between the groups of Fe₄Al₁₃ teeth.

References

[1] Qin Hua, Feipeng Qi, Development of technique of hot-dip aluminizing for iron and steel parts, Materials for Mechanical Engineering 19 (1) (1995) 32 (in Chinese).
[2] Peng Zhang, Study on steel-aluminum solid–liquid bonding, Doctoral Dissertation of Northeastern University, vol. 3, 1998 (in Chinese).
[3] V.I. Dybkov, Interaction of 18Cr–10Ni stainless steel with liquid aluminum, Journal of Materials Science 25 (1990) 3615.
[4] Weijiang Qian, Wengui Gu, Inhibitory action of Si on growth of interfacial compound layer during hot-dip aluminizing, Acta Metallurgical Sinica 30 (9) (1994) 404.
[5] Jun Guo, Yuankang Wu, Investigation on mechanical properties and corrosion resistance of aluminum coated low carbon steels, Materials for Mechanical Engineering 19 (5) (1995) 20 (in Chinese).