

Bonding of Aluminium to Low Carbon Steel using an Overcasting Process

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Abstract

To reduce the weight of a vehicle and improve its fuel efficiency, it is preferable to produce its body in aluminium in place of steel. However, designs may require hybrid structures of aluminium and steel, and there remains a challenge to make a sound bond between the two metals due to their differences in physical, mechanical and metallurgical properties. In the present work, the effect of a zinc coating on the diffusion behaviour between liquid aluminium and a steel substrate was studied. A cost-effective overcasting process was used to cast commercially pure aluminium around uncoated mild steel and 20 μm thick zinc coated steel samples. A reaction layer of similar composition and crystal structure was found between the aluminium and the steel in both cases. SEM-EDS characterisation showed that the reaction layer consisted of 73 at.% aluminium and 28 at.% iron. Moreover, EBSD analysis confirmed that the reaction layer corresponded to the Al_3Fe_4 phase. The thickness of the reaction layer increased with the presence of the zinc coating as compared to uncoated steel sample. The reason for enhanced reaction layer thickness is believed to be caused by improved wetting of molten aluminium on the zinc coated steel.

Keywords: Steel-aluminium, bonding, EBSD, overcasting

1. Introduction

While one of the approaches to mass reduction in the automotive industry is centred around the use of aluminium, it is costly to manufacture an automobile mainly from aluminium parts. So, a combination of high strength low-cost steel and lightweight aluminium in an automotive structure is considered to save mass and keep manufacturing cost low. It is still challenging to perform a sound bond between steel and aluminium due to their different thermal properties such as melting point, coefficient of thermal expansion and thermal conductivity, as well as the formation of brittle intermetallic (IMC) compounds.

The interaction between aluminium and iron at elevated temperatures occurs in different bonding processes. These processes include solid state (eg. diffusion bonding [1], ultrasonic spot welding [2], resistance spot welding [3], roll bonding [4] and soldering [5]) and liquid state (eg. Laser welding [6]-[8], resistance welding processes, laser-tungsten welding[9]) methods. However, in the overcasting process one metal is kept in solid state, while the other metal is in liquid state and a reaction zone is formed across these two metallic components. Overcasting process offers high efficiency and low manufacturing cost as compared to other methods used previously.

The main factors to maintain a sound bond are to control the types and dimensions of IMCs. So, researchers

have focused on the kinetics of intermetallic compound layer formation [10]. It has been found that the growth of the IMC layers is controlled by mass diffusion [11]. Previous studies have shown that the interfacial strength can be improved by controlling the IMC layers between aluminium and steel produced in bonding processes, such as welding or coating. Fe_2Al_5 and FeAl_3 are two IMCs that have been found to form at the interface of an aluminium-steel bond [12]. However, FeAl_2 is produced at the interface when mild steel is hot dipped into molten aluminium, and the phases of the reaction layer change gradually [12].

Traditional kinetic studies on the interfacial IMC layers are performed on samples subjected to isothermal heat treatment operating over a period of time at a constant temperature. However, in the present research overcasting of molten aluminium around steel was used as an alternative method to produce a bond, and so the IMC layer is formed under continuous cooling and not under isothermal conditions. This work is concerned with the study of the IMC reaction layer formed during overcasting of aluminium around steel with and without a zinc coating.

2. Overcasting

After the overcasting the molten aluminium around of $10 \times 1.4 \times 100$ mm steel plates with and without zinc coating (20 μm thick), it was allowed to cool down to room

temperature. The samples were sectioned through the steel plate parallel to the aluminium-steel bond interface. Table 1 shows the chemical composition of the starting aluminium and steel materials used in this work and Figure 1 shows the measured cooling rate for the overcasting process. The average cooling rate of both samples was measured as 5.7 °C/s in the temperature range from 700 °C to 400 °C. Detailed information of the overcasting experimental procedure are found in reference [13].

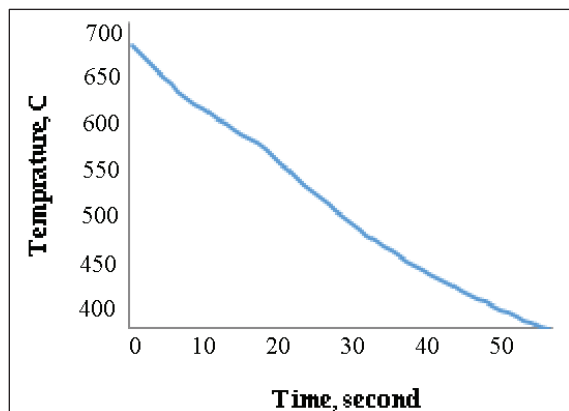


Figure 1: Cooling curve of the both of the samples.

The overcast aluminium-steel samples were prepared for metallographic examination using a combination of scanning electron microscopy (SEM), energy dispersive x-ray analysis (EDS) and electron backscatter diffraction (EBSD) to characterise the reaction layer between aluminium and steel regions. The Kikuchi patterns produced from EBSD were analysed using Team™ software.

Table 1: Composition of the overcast aluminium and the solid steel feature (mass fraction %).

Alloy	Si	C	Mn	Ti	Fe	Al
Aluminium	0.3	0.0	0.0	0.01	0.07	Bal.
Steel	0.05	0.07	0.26	0.3	Bal.	0.4

3. Microstructure

SEM observations revealed the reaction layer formed at the interface of the dissimilar joint. Figures 2a and 2b show typical microstructures of the interface between aluminium and steel with and without the zinc coating, respectively.

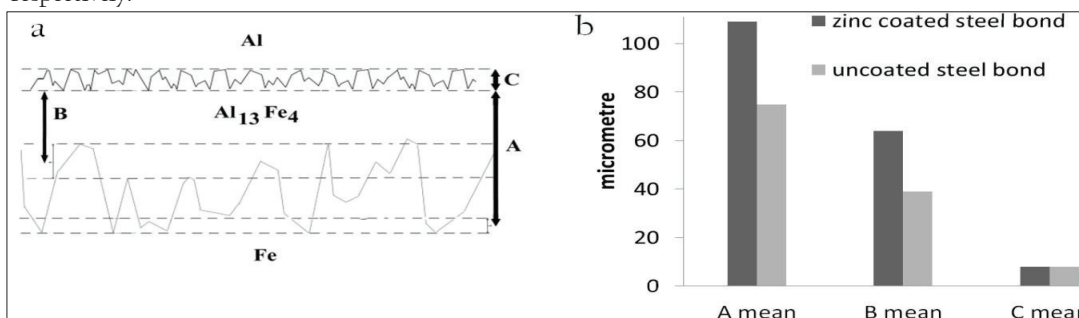


Figure 3: (a) Schematic diagram of the interface of the bond between the steel and the overcast aluminium, showing the three parameters A, B and C used to describe the thickness of the reaction layers; (b) a chart showing the thickness parameters A, B and C for aluminium overcast around steel with and without zinc coating.

In either image, a reaction layer was observed at the aluminium-steel interface and no cracking was detected. The interfacial reaction layer exhibited various morphologies across the sample thickness. In both cases, the reaction layer had a coarse finger-like morphology adjacent to the steel and a fine morphology towards the aluminium side. Although the reaction layer formed in the aluminium interface exhibited a near-planar front, the steel side of the interface is full of perturbations.

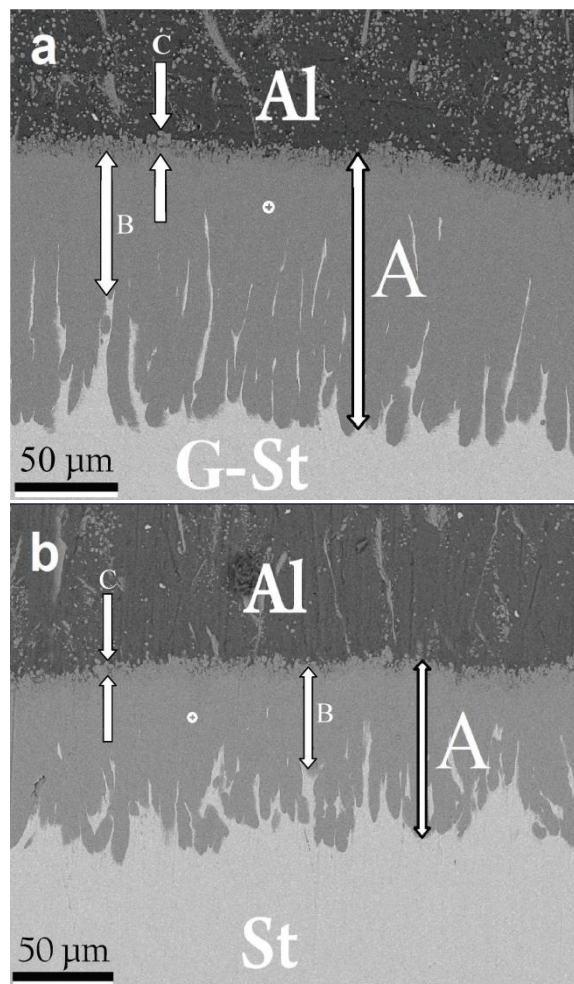


Figure 2: SEM micrographs showing the bond between (a) zinc coated steel and aluminium and (b) uncoated steel and aluminium. The white circles show where EDS and EBSD point analysis were carried out.

It is also seen from Figures 2a and 2b that there is a significant difference in thickness of the reaction layer formed in the samples with and without using the zinc coating. The reaction layer was found to be thicker for the sample with the zinc coating as compared to the uncoated sample.

As described in Figure 3a, the IMC reaction layer between steel and aluminium is defined by different parameters. Parameters A and B are the average maximum and minimum of the diffusion length of the aluminium into the steel and C is a measure of the roughness of the interface near the aluminium side respectively. Figure 3b is a chart showing the thickness of the reaction layers, in terms of parameters A, B & C, for aluminium overcast around steel with and without a zinc coating. Each parameter reflects the mean of 10 measurements of the related area. It is clear, from Figure 3b that the thickness of the reaction layer, and thus the diffusion length of

aluminium into steel, was greater when aluminium was overcast around steel with a zinc coating. This is believed to be attributed to the improved wettability of molten aluminium on zinc coated steel as reported by Gartzon [11], which resulted in enhancement of contact between liquid aluminium and solid steel to facilitate increased diffusion. Conversely, there was no apparent difference in the reaction layer thickness (C) on the aluminium side. The compositions of the reaction layers were determined using EDS. Figure 4 shows the EDS spectrum collected from the reaction layer of the bond between aluminium and zinc coated steel, marked by a white circle in Figure 2a. The reaction layer consisted of 73 at.% aluminium and 27 at.% iron. A similar composition of the reaction layer was also found in the bond between aluminium and uncoated steel in the region marked by a white circle, as shown in Figure 2b.

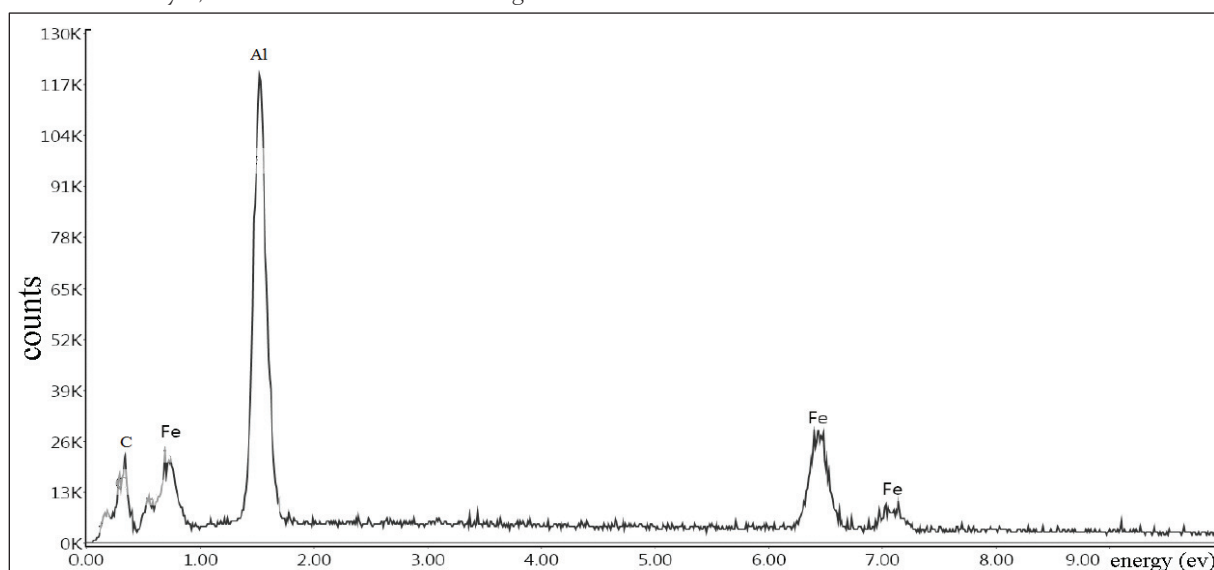


Figure 4: EDS spectrum of the intermetallic phase layer between aluminium and Zn coated steel at a region marked by a white circle, as shown in Figure 2a.

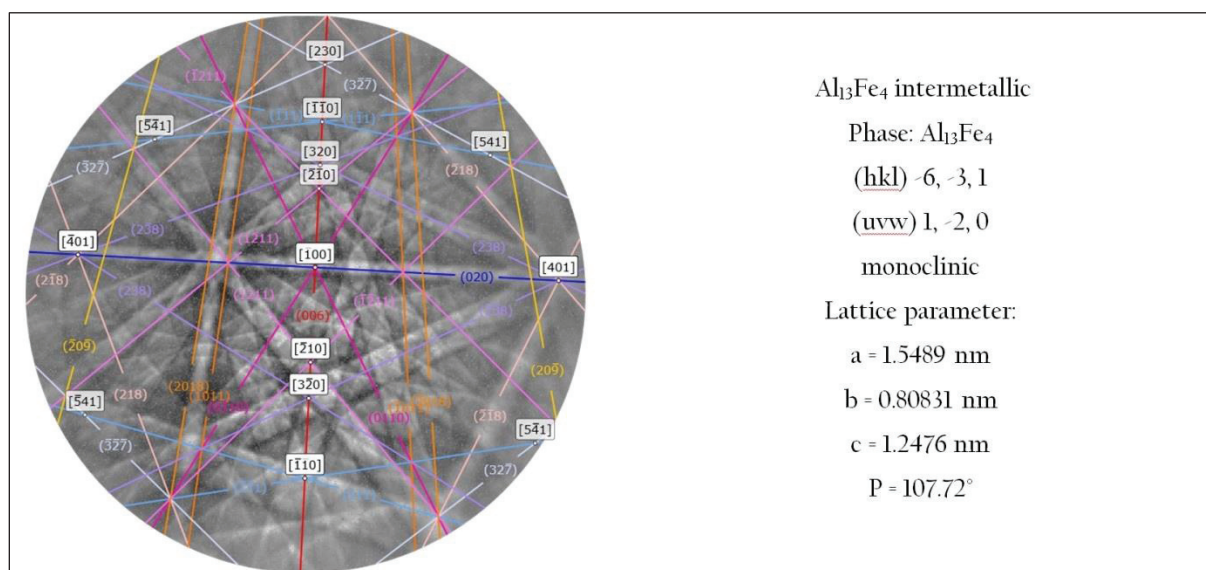


Figure 5: Indexed Kikuchi pattern from the intermetallic reaction layer, demonstrating the formation of the $\text{Al}_{13}\text{Fe}_4$ intermetallic phase, which was apparent in both of the samples.

4. EBSD studies

EBSD analysis confirmed that the crystal structure of the reaction layer was the same in each case. Figure 5 shows a typical Kikuchi pattern from the reaction layer found in both samples. It was indexed to correspond with $Al_{13}Fe_4$ intermetallic phase. Both EDS and EBSD analysis confirmed that the $Al_{13}Fe_4$ intermetallic phase formed at the interface when aluminium was overcast around steel irrespective of the presence of a zinc coating.

5. Summary

The present study investigated the relative growth of the reaction layer of the bond between overcast commercially pure aluminium and mild steel with and without a zinc coating. The reaction layer was found to be $Al_{13}Fe_4$ intermetallic phase in both cases, as confirmed by EBSD and EDS. However, the growth of the reaction layer was found to be influenced by the presence of the zinc coating, which improved wettability between liquid aluminium and steel, promoting the diffusion of aluminium into steel to increase the thickness of the intermetallic reaction layer as quantified by the diffusion length of aluminium into the steel (e.g. A and B parameters).

Acknowledgements

The authors wish to thank the Worshipful Company of Tin Plate Workers alias Wire Workers for financial support.

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