

# *Studies on the Rate of Growth of Alloy Layer of Aluminized Steel*

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## **I. Introduction**

For the production of aluminized steel by the hot dipping method, steel pieces are dipped into molten Al or molten Al alloy. In this case, the time of dipping, temperature of dipping, and the nature of the dipping baths affect the mechanical, physical, and chemical properties of the finished products to a considerable degree. The author reported before partly on the basic effects of these. Present studies were performed to examine the view that the most important factor that affects the various properties of the products is the state of the alloy layer formed between Fe and Al. When a solid steel is brought into contact with molten Al, an Fe-Al alloy is formed at the interface accompanied by the diffusion of Fe into molten Al. Obinata et al.<sup>1)</sup> studied on this diffusion quantitatively on various steels, cast iron, and special steels. On the growth rate of the alloy layer, E. Gebhardt<sup>2)</sup> examined for the couple of Armco iron and an Al alloy added with several percents of various elements. The author studied on the effect of carbon content of the steel on the growth of the Fe-Al alloy layer.

## **II. Preparation of samples**

Table 1 shows the composition of the carbon steels used as specimens. Each

Table 1 Chemical composition of specimen

No	C (%)	Si (%)	Mn (%)	P (%)	S (%)
C 1	0.09	0.35	0.51	0.018	0.020
C 2	0.17	0.27	0.52	0.014	0.024
C 3	0.51	0.23	0.50	0.026	0.019
C 4	0.85	—	—	—	—
C 5	0.95	0.35	—	—	—

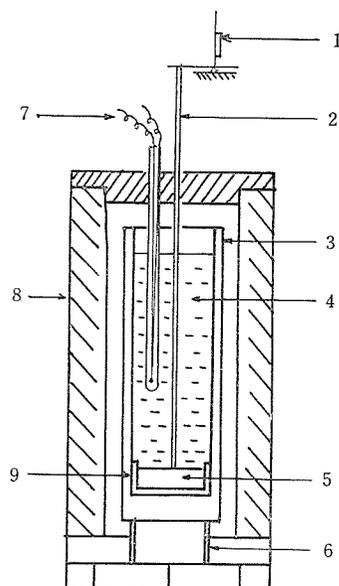
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of these specimens was finished in the shape of a disk, 25 mm in diameter and 5 mm in height. The disks were polished and degreased. The purity of Al used as a solvent was 99.99 %. These materials were used for the study on the reaction between carbon steels and molten Al. It is natural that the results obtained with pure Al only are different from those obtained with Al alloy. When a foreign element is added to Al, most of the metallic element promote the growth of the alloy layer. On the other hand, Si and Mg are known to suppress the growth.

### III. Experimental methods

The experimental apparatus was constructed as shown in Fig. 1. A graphite Tamman crucible containing a specimen was placed on a quartz plate and was heated by an electric furnace. The lower end of the measuring bar was in contact with a sample. A mirror was attached to the top of the bar. With the formation of the alloy layer on the steel surface, the bar was pushed upwards. Then the mirror was tilted. The inclination was measured by the reflexed light through a telescope equipped with a scale.

Degreased samples were placed in a graphite crucible as shown in Fig. 1 and held at 800°C. Before the heating, 10 g flux was scattered on the steel specimen surface in the graphite crucible to prevent the oxidation of the sample and to promote the diffusion between Fe and Al. The flux cut off the contact between air and the sample surface. The flux used for this purpose was a mixture of KCl and LiCl in a weight ratio of 4 : 1. The result obtained by the use of the flux was quite different from that obtained without the use of the flux. Namely, both the amount of Fe dissolved by Al and the growth of the alloy layer were quite different by the presence of a flux. Details will not be discussed here, because Kamimura<sup>3)</sup> reported on the effect of flux on the diffusion between molten Al and solid Fe. In the present experiment, a definite amount of the same flux



1 Mirror  
 2 Measuring Bar  
 3 Graphite Crucible  
 4 Molten Aluminium  
 5 Carbon Steel  
 6 Supporter  
 7 Thermo-couple  
 8 Electric Furnace  
 9 Asbest

Fig. 1 The schematic diagram of apparatus.

were used under the same conditions. Now separately prepared 100 g of molten Al at 805°C was poured into the graphite crucible. At the same time, the measuring bar was placed on the steel surface. The movement of the bar was transferred to the mirror for measurement. The lower end of the measuring bar, namely, the end which is in contact with the specimen surface, was very narrow in area as shown in Fig. 1. Therefore, the diffusion between molten Al and steel was ignored. When the measuring bar was too heavy, the growth or formation of the alloy layer was hindered and a different phase was possibly formed. Therefore, the weight of the bar was made less than several grams in this experiment.

Microscopic examination of the sample after the measurement indicated no anomaly. For the measurement of the alloy layer, E. Scheil (Fe and molten Zn) and E. Gebhardt et al. (Fe and molten Al) attached a dial gauge to the measuring bar to express the growth of the alloy layer directly on a scale. Okamoto et al. used an optical lever for the experiment on Fe and molten Zn. The author adopted the latter method to minimize the weight given to the alloy layer. By the measurement of the growth of the alloy layer, attention was paid to keep the temperature at 800°C as exactly as possible, because a slight change in temperature could largely affect the result of measurement.

#### IV. Experimental results

As shown in Figs. 2 and 3, the growth of the Fe-Al alloy layer is faster with lower carbon steels. On the contrary, the growth is suppressed by the increase in the carbon content. Figs. 2 and 3 show the data obtained by the use of the measuring bar and the data obtained by measuring the thickness of the alloy layer with a metallograph in a solidified specimen, which was taken out of the furnace directly after 2 hrs. and cooled. In Fig. 3, the data between the beginning and the end of the measurement were obtained by approximation with reference to the value obtained by microscopic measurement after solidification. Therefore, the data are not precise enough. Comparison of Fig. 2 with Fig. 3 shows that a considerable difference is present between the values obtained by the measuring bar and those obtained by microscopic determination. Namely, the growth data obtained by the apparatus shown in Fig. 1 do not give the true thickness of the alloy layer formed on the specimen surface.

Now it is assumed that Fe dissolved into molten liquid in an amount equivalent to form an alloy layer,  $x$  mm thick. The thickness obtained by the measuring bar and that obtained by a microscope are expressed by  $h$  and  $h_{\text{Fe-Al}}$ , respectively.  $h_{\text{Fe}}$  gives the thickness of Fe consumed for the formation

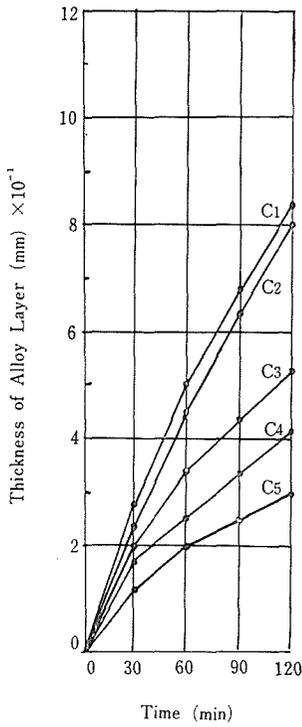


Fig. 2 Values are obtained directly by the author apparatus, using pure aluminium and carbon steel.

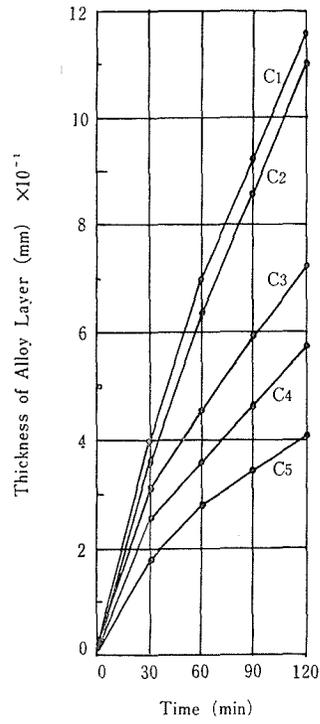


Fig. 3 Values are obtained in directly by the microscopy, using pure aluminium and carbon steel.

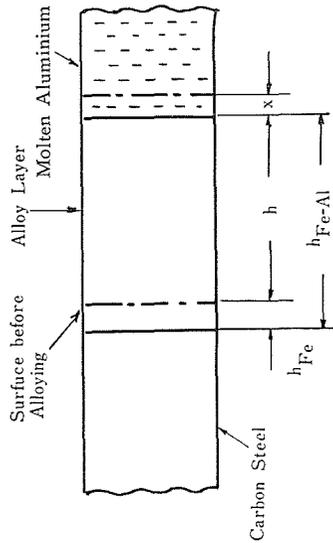
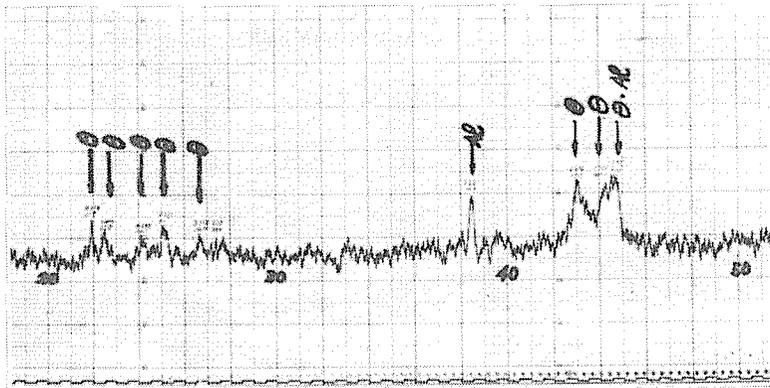
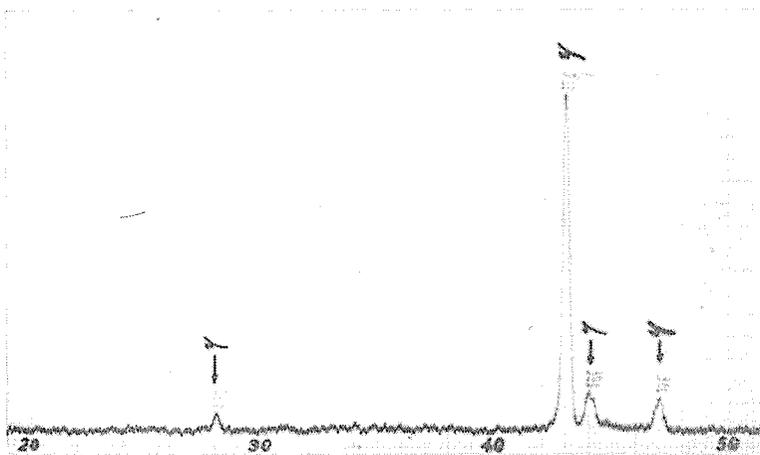


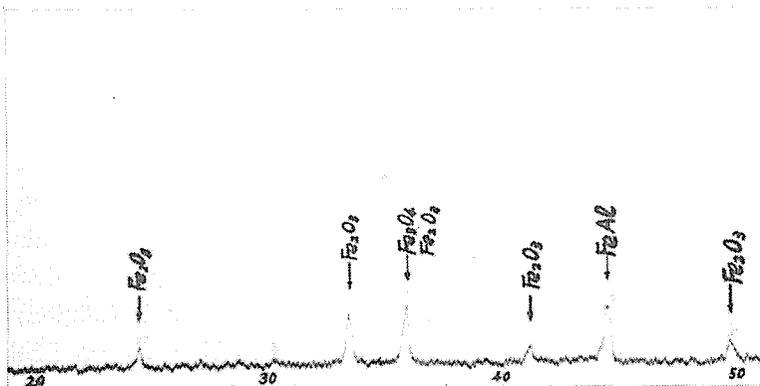
Fig. 4 The schematic diagram of alloy layer.



- (a) At the beginning of heat tests, the aluminium layer of this aluminized specimen was the thickest of all specimens. The specimen was cooled in furnace after diffusion heat-treatment at 500°C, for one hour and then cooled in furnace after diffusion heat-treatment at 800°C, for two hours.



- (b) At the beginning of heat tests, the aluminium layer of the specimen was thinner than specimen (a).



- (c) The specimen removed the aluminium layer from coating before heating and it was treated in the same method as (a).

Fig. 5 X-ray diffractograms of the coating layer of aluminized steel in various states. Intensity is shown on vertical scale, and diffraction angle  $2\theta$  is shown transverse scale.

Table 2 Relation between the value of the diffusion layer and calculated value of the iron which is melted into molten aluminium

No	$h_{\text{Fe-Al}}$ (mm)	$h$ (mm)	$h_{\text{Fe}}$ (mm)	$h/h_{\text{Fe-Al}}$ (%)	$x$ (mm)	$x/h_{\text{Fe-Al}}$ (%)	$x/h$ (%)	$X$ (g)
C 1	1.16	0.84	0.32	72	0.41	35	49	0.32
C 2	1.10	0.80	0.30	72	0.37	34	46	0.29
C 3	0.73	0.53	0.20	73	0.25	34	47	0.20
C 4	0.58	0.42	0.16	72	0.20	34	48	0.15
C 5	0.41	0.30	0.11	73	0.13	32	43	0.10

of the Fe-Al layer from the specimen, namely, the carbon steel. The relation is expressed as shown in Fig. 4. Then the volume of the alloy layer is given by

$$V_{\text{Fe-Al}} = \pi r^2 (h_{\text{Fe-Al}} + x)$$

Assuming that the alloy layer consists of  $\text{FeAl}_3$  and its specific density is 3.9, the weight of the alloy layer is given by

$$M_{\text{Fe-Al}} = 3.9 V_{\text{Fe-Al}}$$

The weight of Fe consumed for the alloying is  $7.8\pi r^2 h_{\text{Fe}}$ , where 7.8 is the specific gravity of Fe. Then following equations hold:

$$\begin{aligned} 7.8\pi r^2 h_{\text{Fe}} &= 0.408 M_{\text{Fe-Al}} \\ h_{\text{Fe}} &= 0.204(h_{\text{Fe-Al}} + x) \dots\dots\dots(1) \end{aligned}$$

According to the results of measurement on the sample C1,  $h_{\text{Fe-Al}} = 1.16$  mm and  $h = 0.84$  mm as shown in Figs. 2 and 3. Substituting these values into Eq. (1),  $x = 0.41$  mm is obtained. The calculated value of  $x$  is 0.78 g.

Consequently, 40.8% Fe, namely, 0.32 g Fe was dissolved in 100 g Al. Table 2 summarizes the values thus obtained for various specimens. As is noticed from this table, the values obtained by the measuring bar are only 72-73% of those obtained by microscopic measurement. The amount of Fe, which dissolves into molten bath, decreases with the increase of the carbon content of the specimens. As shown in Fig. 5, when the thickness of aluminium layer is a very large, the alloy layer formed consists mostly of  $\text{FeAl}_3(\theta)$  phase. In the present studies, the thickness of aluminium layer is infinitely large, therefore the most part of the alloy layer must be  $\text{FeAl}_3(\theta)$  phase. Photos. 1-4 show an example of the sample used for the metallographic examination. All of the micrographs show cross sections of specimens solidified after measurement

for 2 hrs. Photos. 1 and 2 show samples C1 and C5, respectively, the bottom is Fe and the top is Al. The white part in between is  $\text{FeAl}_3$ . A considerable difference is noticed in the thickness of the alloy layer of Photo. 1 and Photo. 2, namely, between samples C1 and C5. It is noticed also how columnar large crystal falls off into molten bath from the alloy layer. Photo. 3 is the enlargement of the Al part in Photo. 1. It is noticed that coarse primary crystals of  $\text{FeAl}_3$  are abundant in the vicinity of the alloy layer, but the occurrence of

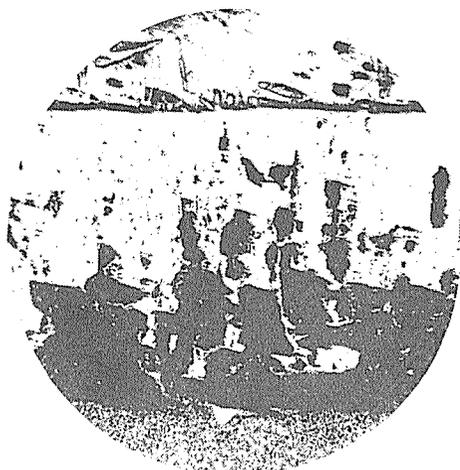


Photo. 1 The upper layer is aluminium side, the lower layer is carbon steel side. White middle part is alloy layer of  $\text{FeAl}_3$ .

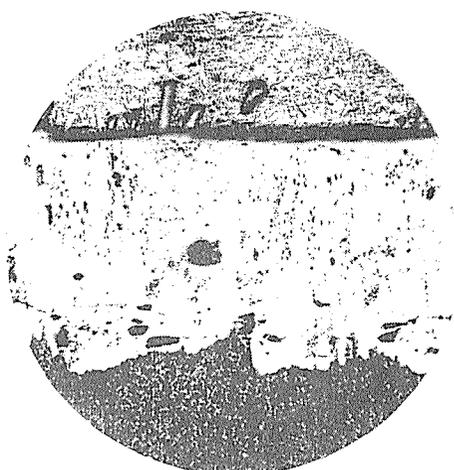


Photo. 2 An alloy layer is thinner than that of Photo. 1.



Photo. 3 Large primary crystals are  $\text{FeAl}_3$  and small needle-like are secondary crystallized  $\text{FeAl}_3$ .

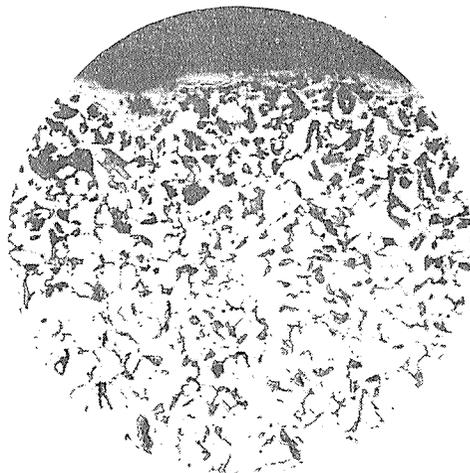


Photo. 4 On the boundaries of alloy layer and carbon steel, a narrow phase along to the boundaries is  $\text{Fe}_2\text{Al}_3$ .

primary crystals decreases as the distance from the alloy layer increases and only acicular  $\text{FeAl}_3$  crystals remain. Photo. 4 shows the enlarged boundary between the alloy layer shown in Photo. 1 and the sample steel. A strange band structure is found along the boundary surface. This band is possibly consists of  $\text{Fe}_2\text{Al}_5$ . This material is hardly noticed in Photos. 1 and 2. It is sure that the structure of  $\text{Fe}_2\text{Al}_5$  band much finer than that of the  $\text{FeAl}_3$  layer.

Therefore, it was assumed by the above calculation that the alloy layer consists only of  $\text{FeAl}_3$ . From this photograph, it is noticed that the carbon content increases with the decrease of the distance from the Fe-Al alloy layer.

## V. Summary

Continuous measurements were made on the growth of the Fe-Al alloy layer formed between molten Al and carbon steels with various carbon contents. The results are summarized as follows:

- (1) The data continuously obtained by a measuring bar correspond to 72-73 % of the values obtained by the use of microscopes after solidification of the melt. This difference is attributable to the decrease of thickness of the Fe specimen consumed for the alloying.
- (2) With the increase of the carbon content, the growth rate decreases. The amount of Fe, which dissolves into the molten bath, also decreases. In the case of the samples solidified after the measurement for 2 hrs., 0.32 % and 0.10 % Fe dissolves when the carbon content is 0.09 % and 0.95%, respectively.
- (3) Most of the grown alloy layer consists of  $\text{FeAl}_3$ . The formation of  $\text{Fe}_2\text{Al}_5$  is presumably very little and is negligible.
- (4) The metallographic structure of the sample steels resembles that of high carbon steels in the vicinity of the boundary between the alloy layer and steel.

## References

- 1) I. Obinata, K. Mutuzaki and S. Terasawa: Journal of the Japan Institute of Metals, 8 (1944), 338.
- 2) E. Gebhardt: Z. Metallk., 44 (1953), 154.
- 3) Kamimura: Iron and Steel, 26 (1940), 813.