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Effect of Dynamic Flow on the Structure of Inhibition Layer in Hot-dip Galvanizing

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The effect of dynamic flow or forced convection were investigated and compared on the formation of inhibition layer, galvanizing and galvannealing reactions through the hot-dip galvanizing simulator with the oscillation of specimen in zinc bath, continuous galvanizing pilot plant with zinc pumping system through the snout and continuous galvanizing operation with Dynamic Galvanizing^{TR} system. The interfacial Al pick-up was not consistent between the results of simulator, pilot plant and line operation, but the morphology of inhibition layer became compact and refined by the forced convection. The growth of Fe-Zn intermetallics at the interface was inhibited by the forced convection, whereas the galvannealing rate would be a little promoted.

Keywords *: dynamic flow, hot-dip galvanizing, galvannealing zinc loath*

1. Introduction

Aluminium in zinc bath is well known to be an important element in hot-dip galvanizing and galvannealing from it's inhibition effect on Fe-Zn intermetallic growth. The thin inhibition layer is mainly composed of Fe-Al or Fe-Al-Zn intermetallics formed at the interface of steel/melt, which is involved to Al pick-up at the initial stage of hot-dip galvanizing. The behavior of Al pick-up is known to be affected by the steel compositions and galvanizing conditions such as line speed, strip entry temperature, bath composition and temperature,[1)] but there would be little research works to investigate the effect of forced convection or dynamic flow.

As the previous works, the influence of flow speed was investigated on the growth of Fe-Al alloy using a hot-dip galvanizing simulator equipped with the cylindrical rotating specimens, which represented that Al amount of Al-Fe alloy were increased with increasing flow speed.[2)] The specialized experiments with a rotating zinc pot suggested that the initial Al take-up at very short immersion times was much higher than supposed in literature, and turbulent conditions resulted in an important decrease of Al take-up without impairing the inhibition quality.[3)] The dynamic effect in galvanizing of high strength steels was investigated with the simulator equipped with zinc stirring system by an axial pump, and the results were that zinc agitation promotes the coating wettability for the steels alloyed with high Mn and Si, and the bath stirring influences the iron/zinc reactivity more significantly in the lower Al content like galvannealing.[4)] ZQ/DynamicGalvanizing^{TR} technology has been claimed to provide the opportunity to produce an excellent GI coating with lower bath Al content close to 0.15% by a turbulent impingement of the melt against the strip during the initial stage of immersion.[5)] However, such previous works didn't deal with the effect of additional forced convection on the interfacial reactivity or Al pick-up connected with the galvanizing or galvannealing reaction.

The present work is tried to understand the effect of forced convection or dynamic flow on the interfacial and subsequent reaction in the lower Al bath condition like galvannealing, comparing through the hot-dip galvanizing simulator with the oscillation of specimen in zinc bath, continuous galvanizing pilot plant with zinc pumping system through the snout and continuous galvanizing operation equipped with Dynamic Galvanizing^{TR} system.

2. Hot-dip galvanizing simulation

The substrate material used in this study were DDQ, TRIP steel with a tensile strength of 590 MPa and DP steel with a tensile strength of 780 MPa as shown in Table

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1. For the precise experiments, 'Multi-purpose Hot-dip Galvanizing Simulator' made by IWATANI Corp. was used. The specimen was oscillated in zinc bath by up and down movements to simulate the forced convection. The oscillation mode was 16 mm of distance at 5 times/sec and the dipping time was 3 seconds. The galvanizing and galvannealing conditions were summarized in Table 2, and the the annealing for heat treatment and galvannealing temperature were different according to the steel types.

The coating weights were 48 g/m^2 for DDQ and 780 DP, and 42 g/m^2 for 590 TRIP. The compositions of coating layers are compared in Fig. 1 for Al content, Al pick-up at the interfacial of the galvanized and Fe content of the galvannealed coating. The differences between the static and oscillating mode were not much except for Fe content of the galvannealed coating, and Al pick-up at the interface for 590 TRIP with higher Si content was much lower than other steels. The alloying degrees of galvannealed coating were decreased in DP and TRIP containing Si despite of higher alloying temperature than DDQ. Fe content were increased by oscillating specimen in zinc bath for DP and TRIP steel, which suggests the structure of inhibition layer to affect the galvannealing reaction would be different between the the static and oscillating mode.

Table 1. Chemical compositions of steel types used

No.	Steel type.	Thickness, mm	C, wt%	Mn, wt%	Si, wt%	Ti, wt%
A	DDQ	0.7	0.002	0.078	-	0.045
B	590 TRIP	0.8	0.105	1.56	1.03	-
C	780 DP	1.2	0.115	2.04	0.234	-

Table 2. Galvanizing and galvannealing conditions for the experiments

Annealing temp.(℃)	Dipping temp.	Pot temp.	Pot Al content.	GA temp. (℃)
(A)840, (B)810, (C)790	480 ℃	457 ℃	0.136 wt%	(A)480, (B)610, (C)500

Fig. 2 shows the surface structure of interfacial layer after removing the upper galvanized coating layer. The differences are not much between the static and oscillating mode, but the oscillation seems to give slightly more uniform and compact structures in DDQ and DP steels. Especially, the coverage and uniformity of interfacial layer were improved by oscillating the specimen in DP steel. The interfacial layer for TRIP steel seems to be very thin and not crystalline, which was somewhat different from DDQ or DP steels with the crystalline type.

The surface morphology for the galvannealed coatings are compared in Fig. 3 with steel types and flow mode. The alloyed surface is mainly composed of refined δ-phase for DDQ steel, and the effect of oscillating specimen would be negligible. In TRIP steel, the coarse grains assumed δ-phase are formed on the surface, which becomes more uniform by oscillating specimen. The assumed η -phase remains on the surface relating to the lower Fe content in DP steel, and the oscillating mode promotes the alloying reaction and gives favorable effect for galvannealing as shown in Fig. 1.

In hot-dip galvanizing simulation to investigate the effect of forced convection, Al content of coating layer and Al pick-up at the interface were similar between the static and the oscillating mode, but there were some differences among the steel types. TRIP steel containing higher Si represented the lower interfacial reactivity with Al of zinc bath. The interfacial or inhibition layer would become more uniform and compact, while the galvannealing reactions were promoted by oscillating specimen, especially notable for DP steel. That could be related with the change in the structure of interfacial layer by the oscillating effect, but the more detailed works would be required. The addi-

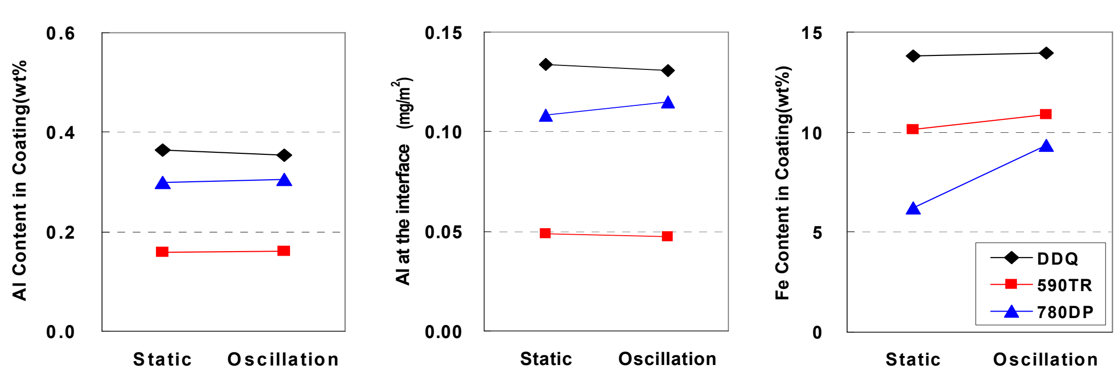

Fig. 1. Comparison of coating composition for the galvanized and galvannealed samples.

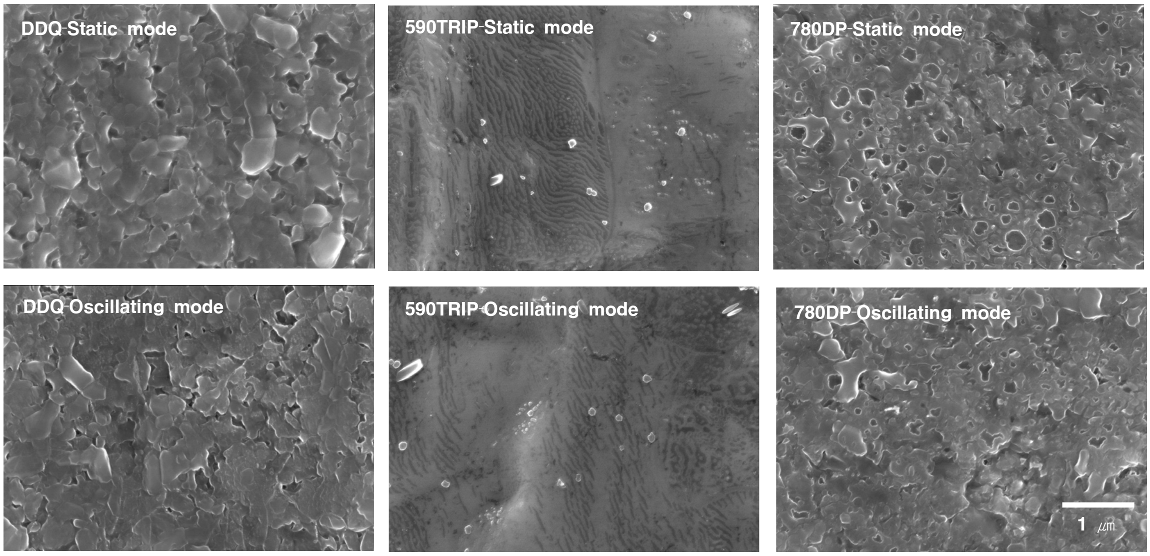

Fig. 2. Surface structure of interfacial layer for hot-dip galvanizing for static and dynamic experiments.

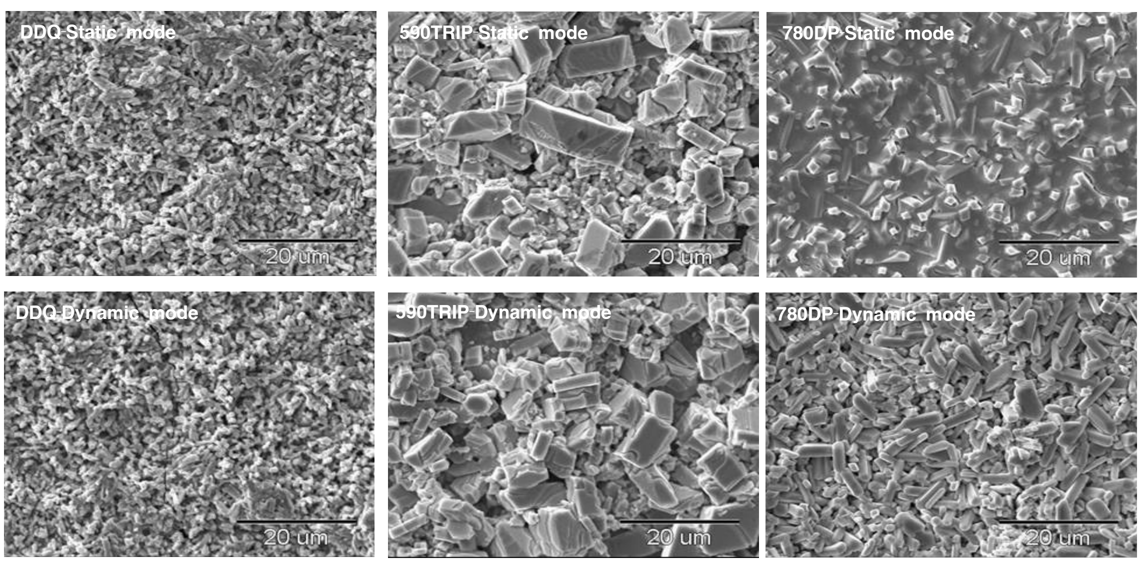

Fig. 3. Surface structure of the galvannealed coating for static and oscillating experiments.

Table 3. General specification of POSCO's CGL pilot plant
*Coil size : 0.4~1.4mm(t) x 100~300mm(w), Max. 3 ton

Line speed	Pretreatment →	Heating furnace →	Zinc pot →	GA furnace →	Cooling
Max. 40mpm	Alkali dip + Electrolytic	Induction + Electric heater	STS 316	Induction, 125KHz	Air + Mist cooling

tion of forced convection or dynamic flow to the strip seems to be more effective in DP and TRIP steel containing high Mn and Si than Ti-stabilized extra low carbon steel for the interfacial Al pick-up and the subsequent galvannealing reaction .

3. CGL pilot test

The general layout and specifications of the pilot plant are summarized in Table 3, which is located at Kwangyang Technical Research Labs. of POSCO. To impart the dynamic flow around the strip entry position in the zinc bath,

Table 4. Test conditions for CGL pilot plant

Line speed	Annealing	Snout pump	FCS temp.	Zinc bath	Galvanneal
30mpm	(A)840 ℃, (B)810, (C)810	3.7KW, 0,800, 1700 rpm	470, 490, 510 ℃	457~459 ℃, Eff. Al 0.127%	(A,C) 480~520, (B) 580~620 ℃

Fig. 4. Snout configuration.

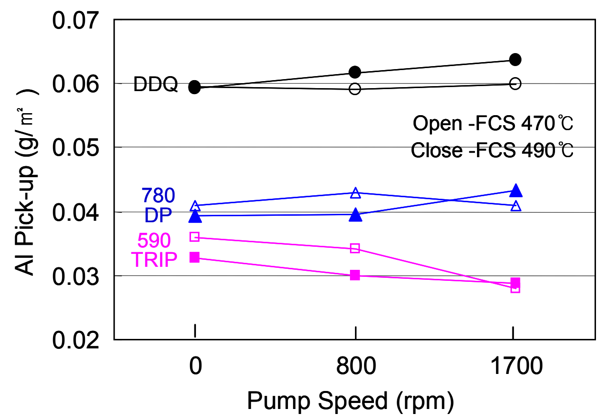

Fig. 5. Variation of Al pick-up at the interface with snout pump speed and strip entry temperature.

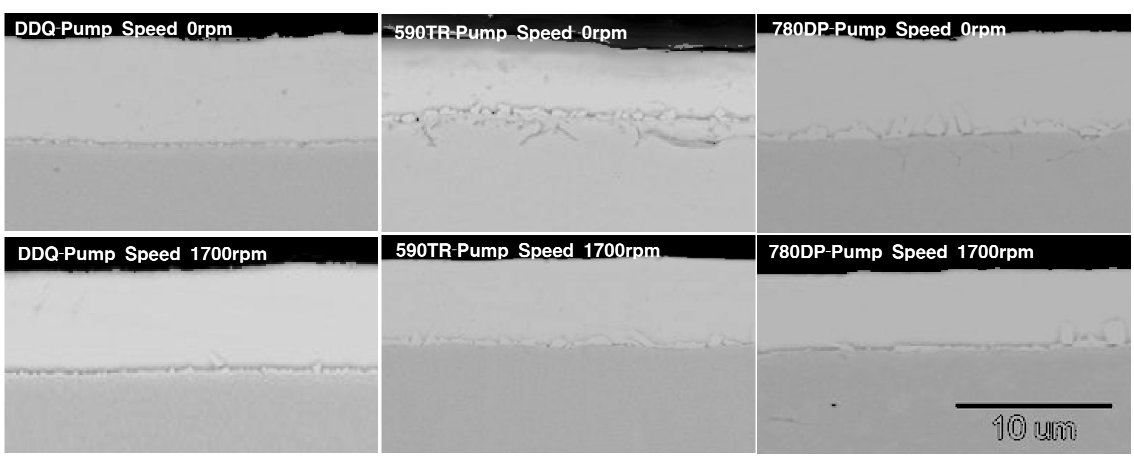

Fig. 6. Structure of galvanized coating layer with and without snout pumping.

the pumps of impeller type were attached to both side walls of snout snorkel as shown in Fig. 4. The steel types of coils tested were same as Table 1 with the width of 200 mm, and the galvanizing and galvannealing conditions are shown in Table 4. The annealing and galvannealing temperature were different according to the steel types as the hot-dip galvanizing simulator tests.

3.1 Analysis of the galvanized coating

The coating weight and Al content were 50~55 g/m^2 and 0.24~0.29 wt.% for DDQ, 30~35 g/m^2 and 0.24~0.34 wt.% for TRIP, and 38~48 g/m^2 and 0.23~0.27 wt.% for DP steel, respectively. The effects of snout pump speed were not much, while the increase of strip entry temperature (FCS temp.) attributed to the increase of coating weight and Al content at the same wiping conditions. Fig. 5 shows the variations of Al pick-up content at the interface, which was slightly decreased with increasing snout pump speed for TRIP, but reversed for DDQ and similar for DP steel. The increase of FCS temp. contributed to a little increase of Al pick-up for DDQ, but was not consistent for TRIP and DP steels. Generally, the increase of interfacial Al pick-up results in the increase of coating Al content, but some different data were noticed.

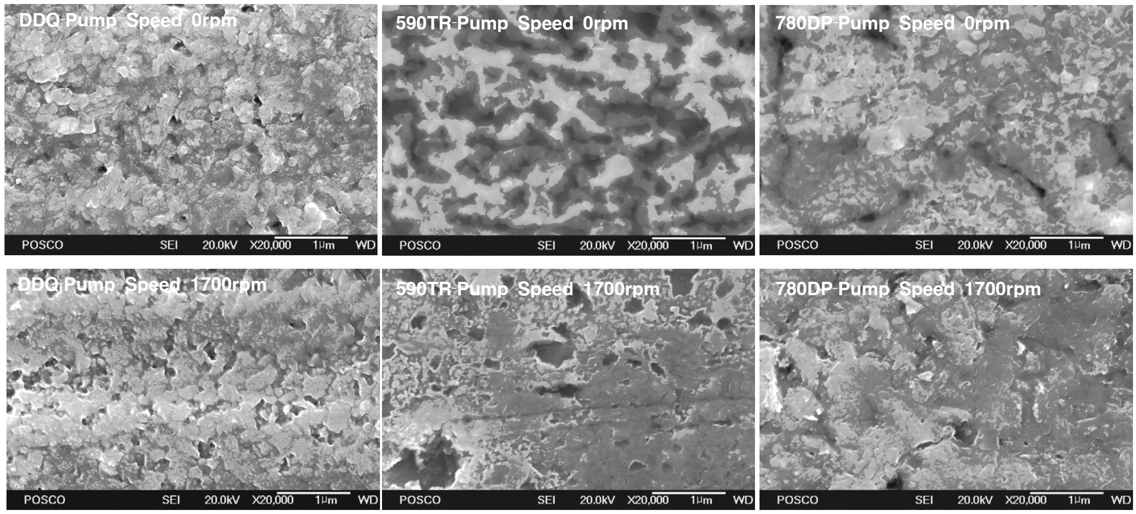

Fig. 7. Surface structure of interfacial layer for hot-dip galvanizing with and without snout pumping.

Fig. 6 shows the cross section view of GI coating layer. The effect of pump speed was not observed for DDQ, but the growth of δ-phase at the interface was observed to be retarded by operating the snout pump for TRIP and DP steels.

Fig. 7 represents the morphology of inhibition layer, which was little changed by snout pumping for DDQ, while it becomes more compact and uniform by applying snout pump for TRIP and DP, especially, the inhibition layer seems to represent the irregular structure without snout pumping for TRIP steel.

3.2 Galvannealing reaction

The galvannealing temperature were different with steel types, especially higher temperature applied for TRIP due to Si effect to retard Fe-Zn alloying, and FCS temperature were controlled to 490 ℃. Fig. 8 compares the alloying degree with pumping speed for 3 different steel types. Fe content of the galvannealed coating was slightly increased with increasing pumping speed, more notable in TRIP steel, which indicates the retarding effect of Si on the Fe-Zn alloying reaction was a little decreased by applying snout pump. On the observation of cross-sectional views for galvannealed coating, the coating structure of TRIP was more different than other steels from the snout pumping, so the unalloyed portion were remained in case of no snout pumping. The powdering property was influenced by Fe content of coating, but the effect of steel type was not observed.

The effect of dynamic flow by snout pumping is more notable in TRIP and DP containing Si and Mn than DDQ on the formation of inhibition layer and the galvannealing behavior, especially the dynamic flow around strip entry

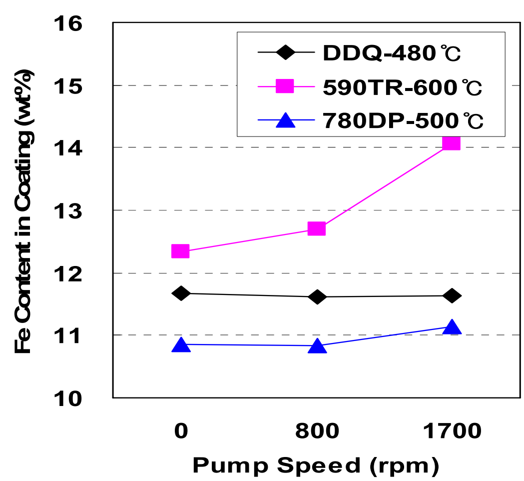

Fig. 8. Comparison of galvannealing rate with snout pump speed and steel types.

into zinc bath would be helpful to improve the coating properties for TRIP steel.

4. Dynamic galvanizing trial

The effect of dynamic flow was evaluated by installing ZQ/Dynamic Galvanizing^{TM} system at #2 CGL of Kwang-yang Steel Works. The system was composed of flow chamber, pumps and cooling tubes supplied by GSI Tech., USA. Since it's difficult to define the testing conditions in line operation, the testing condition was varied on the same coil. Table 5 summarizes the steel types used and galvanizing conditions in the line operation.

For No.A coil test, Al content of the coating were 0.34~0.35 wt.% regardless of testing conditions, and the interfacial Al pick-up were 0.092~0.102 g/m^2, which were slightly increased with increasing zinc pump output. Fig. 9 compares the structure of interfacial layer with FCS temperature and zinc pump output ratio. The inhibition layer would become a little compact with increasing zinc pump output, in which non-layer sites were decreased with higher FCS temperature. The galvannealing reaction was slightly retarded by increasing zinc pump output ratio. For No.B coil test with extra-low carbon steel, it's difficult to explain the differences in the interfacial layer and galvannealing behavior. Fig. 10 shows the interfacial Al content and the inhibition layer morphology with variation of zinc pump output. The differences in the interfacial Al content seems to be decreased between top and bottom side with increasing zinc pump output, but it's difficult to say the differences are meaningful.

Fig. 11 illustrates some data for the relations of Al content in the zinc bath with Al content of the coating layer, which were obtained from the galvannealing operations for conventional and Dynamic Galvanizing^{TR} process tried at #2 CGL of Kwangyang Steel Works. The DG^{TR} process can impart the dynamic flow during the initial stage of

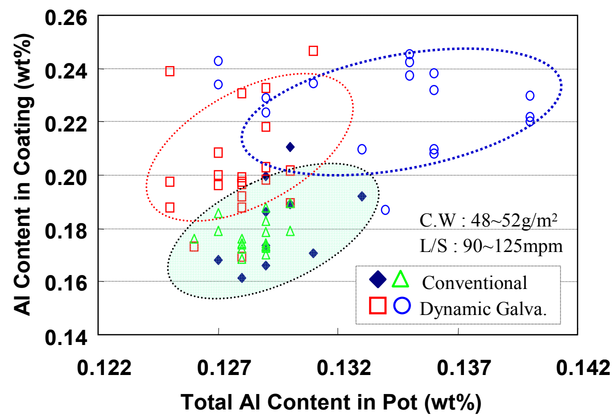

Fig. 11. Relations of Al content in zinc bath with Al content in coating layer.

Table 5. Testing conditions of line operation for evaluation of dynamic flow

No.	Steel type.	Line speed	FCS temp.	Zinc pot temp.	Al content	Zinc pump output
A	CQ, 1mmt	80 mpm	480~520℃	455℃	0.135 wt.%	5, 25, 40%
B	340BH, 0.7mmt	90 mpm	475℃	457℃		10, 50, 80%

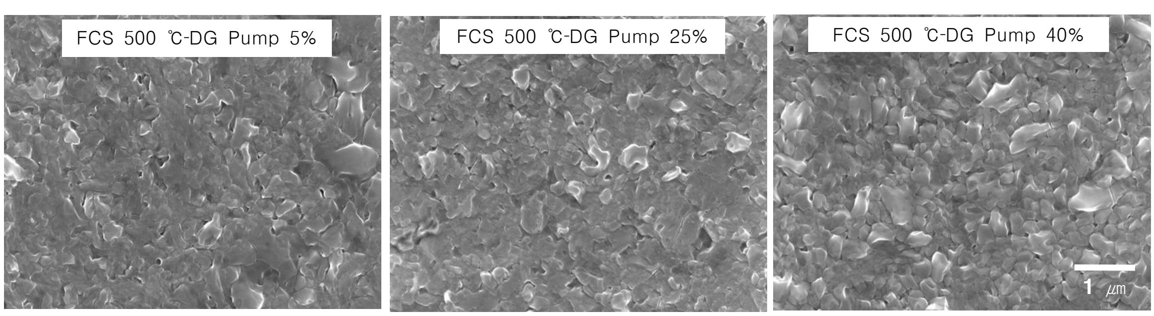

Fig. 9. Surface structure of inhibition layer with zinc pump ratio and FCS temperature (No.A coil)

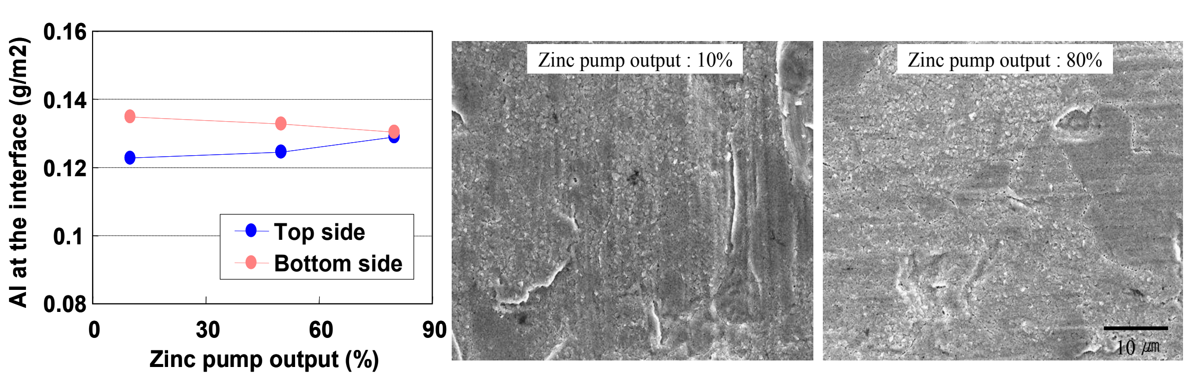

Fig. 10. Al pick-up at the interface and surface structure of interface layer with zinc pump ratio (No.B coil).

Table 6. Summary of the effect by introducing dynamic flow or forced convection

Method	Steel type	Inhibition layer	Al pick-up	Fe-Zn growth	GA reaction
Simulator	DDQ (Extra Low C)	compact	similar	Fe-Zn growth in zinc bath inhibited	a little increase
	590TRIP, 780DP	compact, uniform	similar		a little increase
Pilot test	DDQ	similar	similar		similar
	590TRIP, 780DP	compact	a little decrease		a little increase
Line trial	CQ (Low C)	compact	a little increase		not consistent
	340BH (Extra Low C)	similar	similar		similar

strip immersion into zinc bath, which would contribute to the increase of Al content in the coating layer compared to the conventional process without the dynamic flow effect, although other operating conditions could be affected such as FCS temperature, line speed, bath temperature, and etc.

5. Summary

The effect of dynamic flow or forced convection were investigated and compared on the formation of inhibition layer, galvanizing and galvannealing reactions through hot-dip galvanizing simulator, continuous galvanizing pilot plant and continuous galvanizing line equipped with ZQ/Dynamic Galvanizing System^{TR}., which would be summarized as the following table.

The interfacial Al pick-ups were not consistent between the results of simulator, pilot plant and line operation, but the surface structures of inhibition layers became compact and refined by introducing the forced convection or dynamic flow. The interfacial growths of Fe-Zn intermetallics were inhibited, whereas the alloying rate for galvannealing would be a little increased by the dynamic effect. The difference of inhibition layer and galvannealing rate from the dynamic floe was more dominant, especially in case of TRIP steel, which indicates the retarding effect of Si on the galvannealing rate decreased. Such dynamic effects in zinc bath could be an alternative to improve the galvanizing and galvannealing reaction for high strength steels with higher Mn and Si content. It would be not easy to explain the effect of dynamic flow in the operating line explicitly due to the various process conditions concerned, but a little differences from the conventional process were confirmed such as the interfacial Al pick-up increased, the compact strucure of inhibition layer and the growth of Fe-Zn intermetallics retarded.

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