Development of the 550MPa Grade Hot-dipped Galvanized HSLA Steel

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High-strength low-alloy (HSLA) steel has been widely used as structural parts in automobiles. Since the requirement of weight reduction and anticorrosion of body-in-white, the demand of galvanized HSLA steel with the highest 550MPa grade is rising. In this study, galvanized HSLA steel with 550MPa yield strength was developed. The effect of grain size and precipitation on the microstructure and strength and the zinc coating quality of galvanized cold-rolled strip were discussed. The results show that the mechanical property of 550MPa yield strength and 13% elongation can be achieved by adopting both fine grain strengthening and precipitation strengthening. The ideal microstructure of steel can be achieved by controlling the cold rolling and annealing processes, which lead to a ferrite matrix with a grain size of 2~5μm and precipitations with a diameter of 20~30nm in the matrix. It also revealed that the annealing temperature has a significant influence on the microstructure and mechanical property, while the reduction ratio of cold rolling and slow cooling temperature have no effect. Moreover, the hot-dipped galvanized HSLA steel with 550MPa grade has a good coating quality.

Keywords: HSLA Steel, Fine Grain Strengthening, Precipitation Strengthening, Galvanized Cold-rolled Strip

1. INTRODUCTION

Corrosion prevention of steels can be achieved by surface coating treatment. Among all of the treatments, hot-dip galvanizing is a popular one due to its barrier protection and galvanic protection(1-3). The galvanized steel has been widely used in everyday products as well as industrial construction. Especially in automobile production, galvanized steel is used as the main component material for the body-in-white(4-5). Among all the body-in-white steels used , high strength-low-alloy (HSLA) steel has been widely used for structural components.

HSLA steel is commonly referring to the steels with an alloy content of less than 5%, while yield strength is higher than 275MPa. This type of steel has excellent weldability, wearbility and formability. The first HSLA steel was developed in the 1970s. The steel had a single alloy element added, such as Cr, Ni or Si. The amount of alloy was in the range of 2~3% and carbon content was more than 0.3%. Considering the requirement of weldability, the carbon content of HSLA steel was controlled by less than 0.2% afterwards(6-7). In recent decades, considering both the high strength and weldability, carbon content of HSLA steel was less than 0.1% while Ti, V, Nb were used as a microalloy in order to refine the grain size of the matrix by forming their carbides or nitrides(8).

Hot-dip galvanized steel strip is produced by a continuous galvanizing line (CGL) dipping the steel strip in a zinc bath at around 460°C. During the dipping process, the diffusion between the steel and liquid zinc occurs and then leads to the formation of brittle and thick Fe-Zn intermetallic layer. Al in the range of 0.12~0.20% is commonly added in the zinc bath to form a thinner Fe-Al intermetallic layer instead of Fe-Zn intermetallic layer for improving the formability of the coating. Due to the annealing process in the CGL being limited by the zinc pot temperature (460°C), the development of galvanized HSLA steel is difficult. Moreover, Mn added in HSLA steel for solid solution strengthening purposes hinders the wettability between the steel strip and zinc bath, which leads to a poor coating quality(9-10).

Since the requirement of weight reduction and anticorrosion of body-in-white has been addressed in recent years, galvanized HSLA steel with the highest 550MPa grade is one of the steels that can fulfill the needs of the automobile manufacturers. In this study, galvanized HSLA steel with 550MPa yield strength was developed. Both the effect of grain size and precipitation on the microstructure and strength and the zinc coating quality of galvanized cold-rolled strip were discussed.

2. EXPERIMENTAL METHOD

2.1 Annealing and hot-dip galvanizing

Table 1 shows the chemical composition of two steel sheets that were used in this study with a thickness gauge of 1.2 mm. Steel sheet samples were prepared from the hot-rolling state and then subjected to cold-rolling and annealing processes. The cold-rolling reduction were in the range of 45~55%. The schematic illustration of the annealing and hot-dip galvanizing is shown in Fig.1. The samples were rapidly heated to 650~850°C (SS) followed by slow cooling to 550~750°C (SCS), rapid cooling to 440~500°C (RCS), and an isothermal process temperature in the range of 440~500°C (LTHS). Six SS temperatures (SS1~SS6) and five SCS temperatures (SCS1~SCS5) were selected from low to high temperatures. Moreover, SS1~SS2 were the temperatures at the ferrite single-phase region and SS3~SS6 were the temperatures at the ferrite-austenite dual-phase region.

Samples after LTHS were consecutively subjected to the hot-dip galvanizing process and then cooled to room temperature. During hot-dip galvanizing, samples were dipped in a zinc bath with Zn-(≦0.2)Al composition at 440~500°C and then taken out from the bath followed by an air knife wiping to control the coating with a thickness of 5~15μm.

2.2 Mechanical characterizations

Samples after galvanizing were cut horizontal to the rolling direction from steel sheets with various heat treatments. These samples were processed into tensile specimens with the specification of ASTM sheet type. Afterwards, they were examined by a tensile test to measure their mechanical properties. The mechanical property requirement of HSLA steel with 550 MPa grade is YS: 550MPa, TS: 650MPa, EL: 13%.

2.3 Microstructure analysis

Samples after galvanizing underwent metallographic examination. They were cut along the rolling direction. After being ground, polished and etched with 3% nital solution, these samples were analyzed by using SEM (Scanning Electron Microscope) and TEM (Transmission Electron Microscope) to observe the phase constitution, grain size and precipitations.

3. RESULTS AND DISCUSSION

3.1 Microstructural and mechanical property of steels at hot-rolling state

The microstructures of steel A and steel B at a hot-rolling state are shown in Fig.2. Both steels have the same ferrite matrix with a low amount of carbides. The grain size for both steels were in the similar range of 2~5μm, since steel A has a slightly larger grain size. The mechanical properties of steel A and steel B are shown in Table 2. Steel B has a higher strength than steel A, however they both can reach the mechanical requirement of HSLA steel with 550MPa yield strength.

Table 1 Chemical composition (in wt%) of steel sheets used in this study

	C	Mn	others
Steel A	0.08	1.2	-
Steel B	0.09	1.5	Ti, V

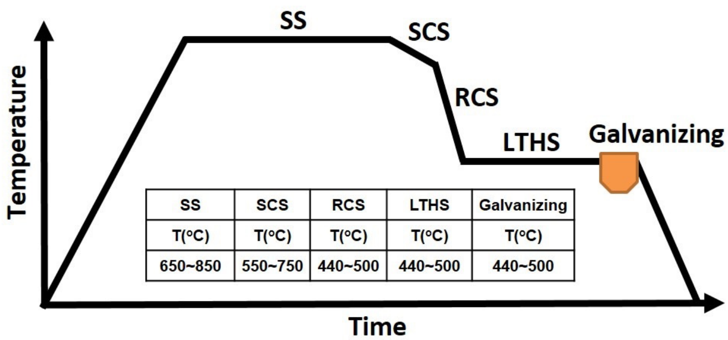

Fig.1. Schematic illustration of heating cycle of the annealing and hot-dip galvanizing

3.2 Mechanical properties of cold-rolled steels after annealing

Hot-rolled samples of A and steel B endured cold-rolling for a 55% reduction and then experienced annealing refers to the heating cycle as shown in Fig.1. The mechanical properties of steel A and steel B after annealing are shown in Table 3 and Table 4, respectively. It can be found that when the SS temperature is controlled at SS5 and SS6, the mechanical properties of steel A is YS: 470~540MPa, TS: 540~590MPa, EL: 13~19%. This

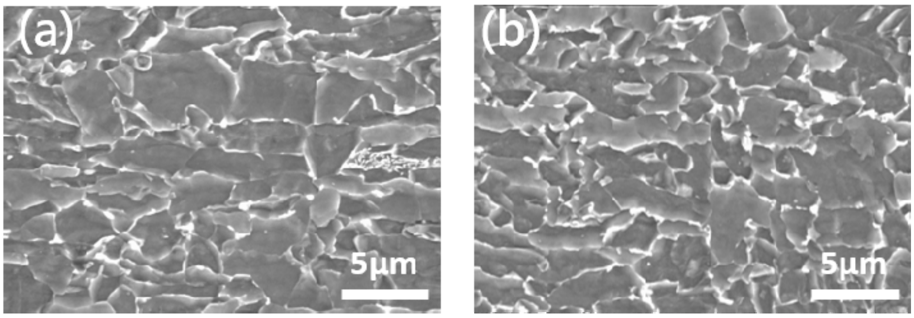

Fig.2. Microstructure of (a) steel A and (b) steel B at hot-rolling state

Table 2 Mechanical properties of steel A and steel B at hot-rolling state

	YS (MPa)	TS (MPa)	EL (%)
Steel A	590	680	15
Steel B	715	810	16

Table 3 Mechanical properties of steel A after annealing

Reduction Rate	SS(°C)	SCS(°C)	Mechanical Property		
			YS(MPa)	TS(MPa)	El(%)
55%	SS1	SCS3	735~470	975~540	9~19
	SS2	SCS3			
	SS3	SCS3			
	SS4	SCS3			
	SS5	SCS3			
	SS6	SCS3			
	SS6	SCS5	485	550	18
	SS6	SCS4	475	540	18
	SS6	SCS2	460	530	20
	SS6	SCS1	480	545	18
45%	SS1	SCS3	915~470	925~540	6~18
	SS2	SCS3			
	SS3	SCS3			
	SS4	SCS3			
	SS5	SCS3			
	SS6	SCS3			
	SS6	SCS5	465	545	19
	SS6	SCS4	465	540	18
	SS6	SCS2	465	535	19
	SS6	SCS1	470	540	17

Table 4 Mechanical properties of steel B after annealing

Reduction Rate	SS(°C)	SCS(°C)	Mechanical Property		
			YS(MPa)	TS(MPa)	El(%)
55%	SS1	SCS3	1065~535	1075~620	1.0~18
	SS2	SCS3			
	SS3	SCS3			
	SS4	SCS3			
	SS5	SCS3			
	SS6	SCS3			
	SS6	SCS5	535	630	17
	SS6	SCS4	530	620	18
	SS6	SCS2	540	620	17
	SS6	SCS1	540	615	17
45%	SS1	SCS3	1035~525	1050~620	4.0~19
	SS2	SCS3			
	SS3	SCS3			
	SS4	SCS3			
	SS5	SCS3			
	SS6	SCS3			
	SS6	SCS5			
	SS6	SCS4	520	615	19
	SS6	SCS2	530	610	20
	SS6	SCS1	535	615	19

result reveals that steel A can not reach the mechanical property requirement of HSLA steel with 550MPa grade. On the contrary, when the SS temperature is controlled at SS5 and SS6, the mechanical properties of steel B is YS: 535~620MPa, TS: 620~685MPa, EL: 13~18%. This indicates that steel B can fulfil the mechanical property requirement of HSLA steel with 550MPa grade when the SS is controlled between SS5 and SS6.

3.3 Effect of process conditions

Based on the above results, steel B was further investigated for understanding the effect of the annealing cycle. By comparing the microstructure and mechanical property, it reveals that steel B is not fully recrystallized when the SS is less than SS4. The fully recrystallized microstructure can be completed when the SS reaches to SS5. On the effect of cold-rolling reduction, it shows that there is no significant effect on the microstructure and mechanical property when the reduction ratio is controlled in the range of 45~55%. SS plays an important role on the grain size of the steel, which caused the grain growth from 1~2μm to 2~8μm when SS increased from SS4 to SS6. On the other hand, SCS has no effect on the microstructure of the steel as shown in Fig.3 and Fig.4.

3.4 Effect of microalloy

Ti and V microalloy added in steel B can restrain the grain size in the range of 2~5μm when SS temperature in annealing was controlled at SS5, which provides fine grain strengthening. Moreover, precipitation strengthening due to the microalloy also introduced the high strength requirement of HSAL steel with 550MPa grade in steel B. The TEM observation of steel B at a hot-rolling state is shown in Fig.5. The precipitations, identified as nano-sized carbides, with 40nm interlayer spacing was produced, which gives a mechanical property that can reach to YS: 715MPa, TS: 810MPa, EL: 16%. In order to adjust the mechanical property to meet the requirement of HSLA steel with 550MPa grade. The nano-sized carbides were subjected to growth by the cold-rolled steel undergoing SS processes during the annealing cycle. This resulted in the degradation of precipitation hardening by increasing the size of carbides to 20~30nm. However, these coarsened precipitates can still have the effect of precipitation and fine grain strengthening for steel possessing high strength and adequate elongation.

3.5 Zinc coating quality

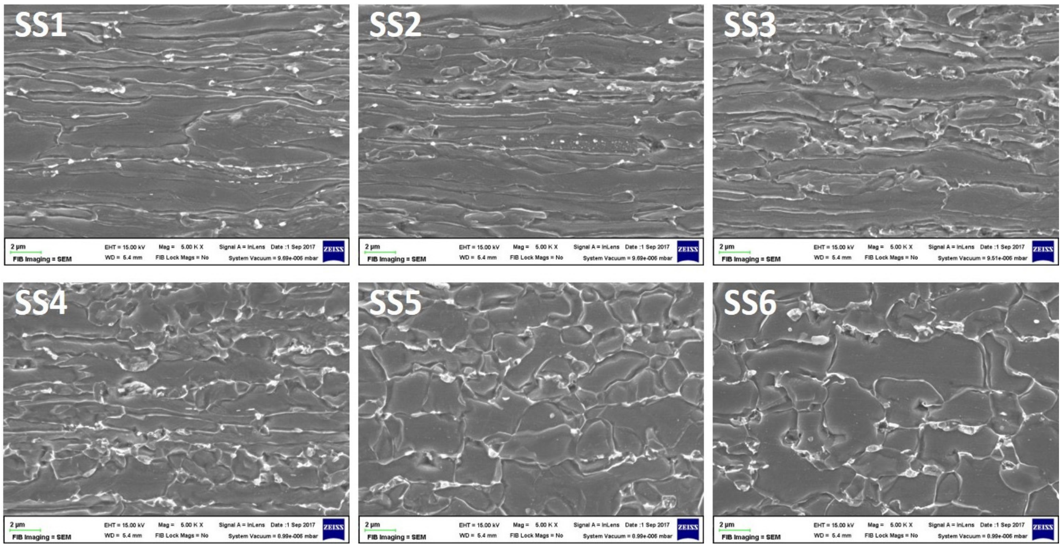

Fig.3. Microstructure of steel B after 45% cold-rolling reduction and annealing at different SS temperature

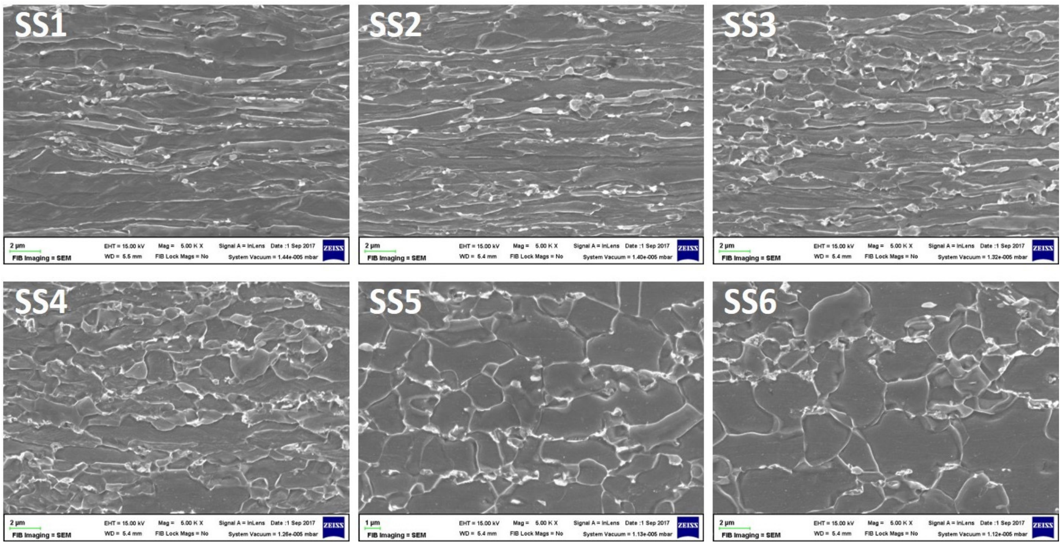

Fig.4. Microstructure of steel B after 55% cold-rolling reduction and annealing at different SS temperature

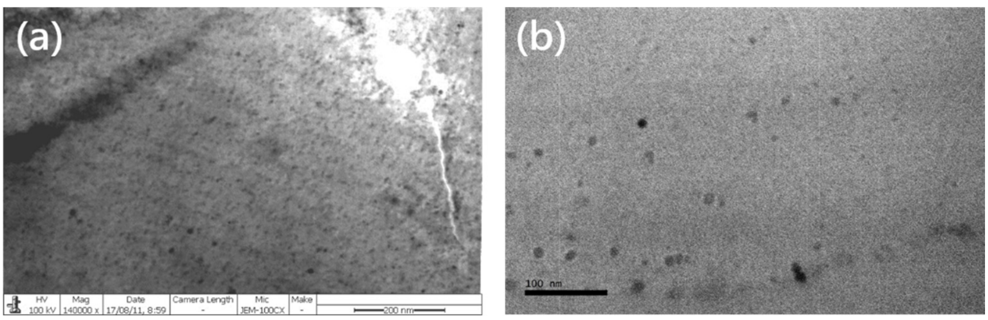

Fig.5. TEM observation of nano-sized carbides in steel B at (a) hot-rolling state and (b) after cold-rolling and annealing

The appearance of steel B after annealing and galvanizing is shown in Fig.6. It reveals that there was no bare spot defects formed in the zinc coating. The 180° bending test shows that the coating has a good adhesion with the steel substrate. The microstructure of the coating reveals that $Fe_2(Al,Zn)_5$ layer, formed at the interface between coating and steel substrate, has a grain size of 150~300nm and the covers over 95% of the steel

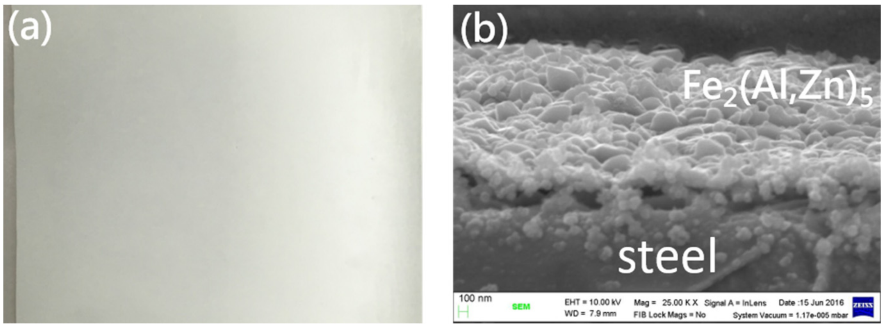

Fig.6. (a) Appearance and (b) microstructure of zinc coating on steel B

substrate surface. This indicates that Mn or microally in steel B would not cause severe annealing oxidation on the steel surface, leading to the steel B having adequate wettability for galvanizing[11-13].

4. CONCLUSIONS

Galvanized HSLA steel with 550MPa yield strength was developed in this study. The effect of grain size and precipitation on the microstructure as well as strength and the zinc coating quality of galvanized cold-rolled strip have been addressed. The mechanical property of 550MPa yield strength and 13% elongation can be achieved when Ti and V microalloyed steel being subjected to cold-rolling and annealing processes. The ideal microstructure of the steel composes of ferrite matrix with a grain size of 2~5μm and precipitations with a diameter of 20~30 nm in the matrix. The developed steel with high strength and excellent elongation was attributed to both fine grain strengthening and precipitation strengthening. The microstructure and mechanical property were dominated by the annealing process, in which the annealing temperature has a significant influence on the microstructure and mechanical property, while both the 45~55% reduction ratio of cold rolling and slow cooling temperature in a range of 550~750°C in the annealing process have no effect. The zinc coating on the galvanized HSLA steel with 550MPa grade has a good coating quality, which shows a bare spot-free surface and good adhesion to the steel substrate.

REFERNCES

1. S. L. Chawla and R. K. Gupta, Materials Selection for Corrosion Control, ASM International, 1993.
2. A. Qaban and S. Naher, Investigation of corrosion resistance of high-strength low-alloy (HSLA) steel in fresh and salt water for pipeline application, AIP Conference Proceedings, 2019, Vol. 2146.
3. R.W. Revie, Corrosion and corrosion control: an introduction to corrosion science and engineering, John Wiley & Sons, 2008.
4. P.K.Mallick, Advanced materials for automotive applications: an overview, Advanced Materials in Automotive Engineering, 2012, 5-27.
5. G.M. Smith, D. Aichbhaumik, G.A. Gronceski and J.J. Brinsky, The Development of High Strength Galvanized Steels for Automotive Applications, Conference: SAE International Congress and Exposition, 1983.
6. L.F. Porter and P.E. Repas, The Evolution of HSLA Steels, JOM, 1982, Vol. 34, 14-21.
7. D.A. Skobir, HIGH-STRENGTH LOW-ALLOY (HSLA) STEELS, Materials and Technologies, 2011, Vol. 45, 295-301.
8. J. Fernández, S. Illescas and J.M. Guilemany, Effect of microalloying elements on the austenitic grain growth in a low carbon HSLA steel, Materials Letters, 2007, Vol. 61, 2389-2392.
9. S. Dionne, J. McDermid, B. Voyzelle, E. Essadiqi, E. Baril and F.E. Goodwin, Galvanizing of Hot Rolled High Strength Grades: Effect of Reheat Temperature and Furnace Atmospheres on Coating Quality, Materials Science and Technology, 2004, Vol 1, 793-805.
10. Q.W. Wu, A.M. Zhao, S. Yao, and Z. Li, Bare Spot Defect on a Hot Dip Galvanized DP Sheet Strip, Materials Science Forum, 2018, Vol. 913, 294-303.
11. K. Ranganathan, J.R. McDermid and F.E. Goodwin, Continuous Hot-Dip Galvanizing of a Third Generation (3G) Advanced Steel, Galvatech 2015 Proceedings, 2015.
12. R. Khondker, A. Mertens and J.R. McDermid, Effect of annealing atmosphere on the galvanizing behavior of a dual-phase steel, Materials Science and Engineering A, 2007, Vol. 463, 157-165.
13. R. Kavitha and J.R. McDermid, On the in-situ aluminothermic reduction of manganese oxides in continuous galvanizing baths, Surface & Coatings Technology, 2012, Vol. 212, 152-158. □