21COE, University of Tokyo ***MMRC Discussion Paper*** **No. 73**

MMRC-F-73

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Fujimoto Takahiro, GE Dongsheng and OH Jewheon

Manufacturing Management Research Center, University of Tokyo

March 2006

東京大学21世紀COE〔センター・オブ・エクセレンス〕
ものづくり経営研究センター

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Abstract

The trade pattern of steel products, especially those for automotive applications in East Asia intrigues us to explore the micro foundation of the so-called comparative advantages of Korea, China and Japan. We propose that the fit of process architecture and the accumulated organizational capability is one underlying force driving the specialization across country borders. Bake hardenable steel sheet and surface-treated steel mainly for automobile's outer panels are two cases under scrutiny, while function-process matrix is tentatively utilized to measure the architectural attributes of steel processing.

Keywords

Process architecture, function-process matrix, organizational capability, comparative advantage, automobile steel sheet, East Asia

Introduction

Among the examples of mutual growth achievement in East Asia, steel making industry bears no more salient feature of competition and cooperation between firms of different nations. In the region that is the most competitive manufacturing base of steel products in the world, China is continuing to be the largest steel producer driven by the robust development of economy, while the Korean representative maker Posco is boasting of the highest profitability and Japanese makers are taking the lead in the field of advanced technology (see Table 1, 2, 3 and Figure 1). Although competition becomes much fiercer in securing iron ores supply and in the final product markets, most companies are enjoying their record high level of profits as joint ventures and extensive technological partnership enter an unprecedentedly active phase. In this paper, rather than addressing a macro picture of steel industry, we focus our attention on the steel sheets for automotive use to examine the comparative advantages of companies in three countries and to explore their micro foundation through analyzing the features of manufacturing processes.

Table 1 Country's Ranking of Crude Steel Production (Million tons)

	Country	Output	Share
1	China	286	26
2	EU15	159.8	16.6
3	Japan	121	11
4	US	99	9
5	Russia	66	6
6	South Korea	44	4
7	Germany	44.8	4.6
8	Ukraine	36.9	3.8
9	India	31.8	3.3
10	Brasil	31.1	3.2

Table 2. Company's Ranking of Crude Steel Production (Million tons)

Company	Output
Arcelor (LUX)	46.9
LNM Holdings (NED)	42.8
Nippon Steel (JAP)	31.4
JFE Steel (JAP)	31.1
POSCO (KOR)	31.1
Shanghai BaoSteel (China)	21.4
US Steel (USA)	20.8
Corus Group (U.K.)	19.9
Nucor (USA)	17.9
ThyssenKrupp (GER)	17.6

Source: IISI Worldsteel, 2004.

Figure 1 Posco's Profitability

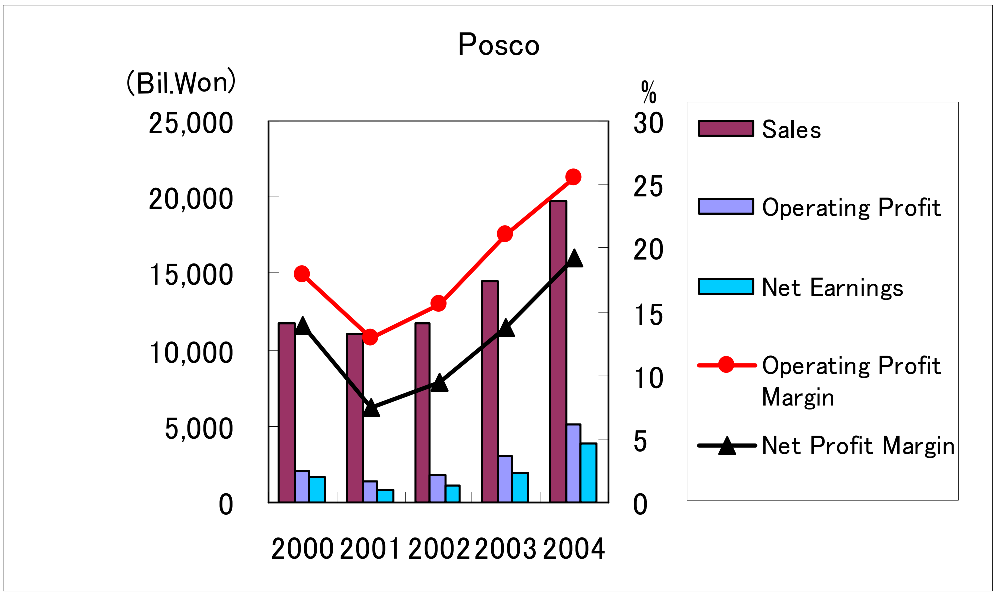


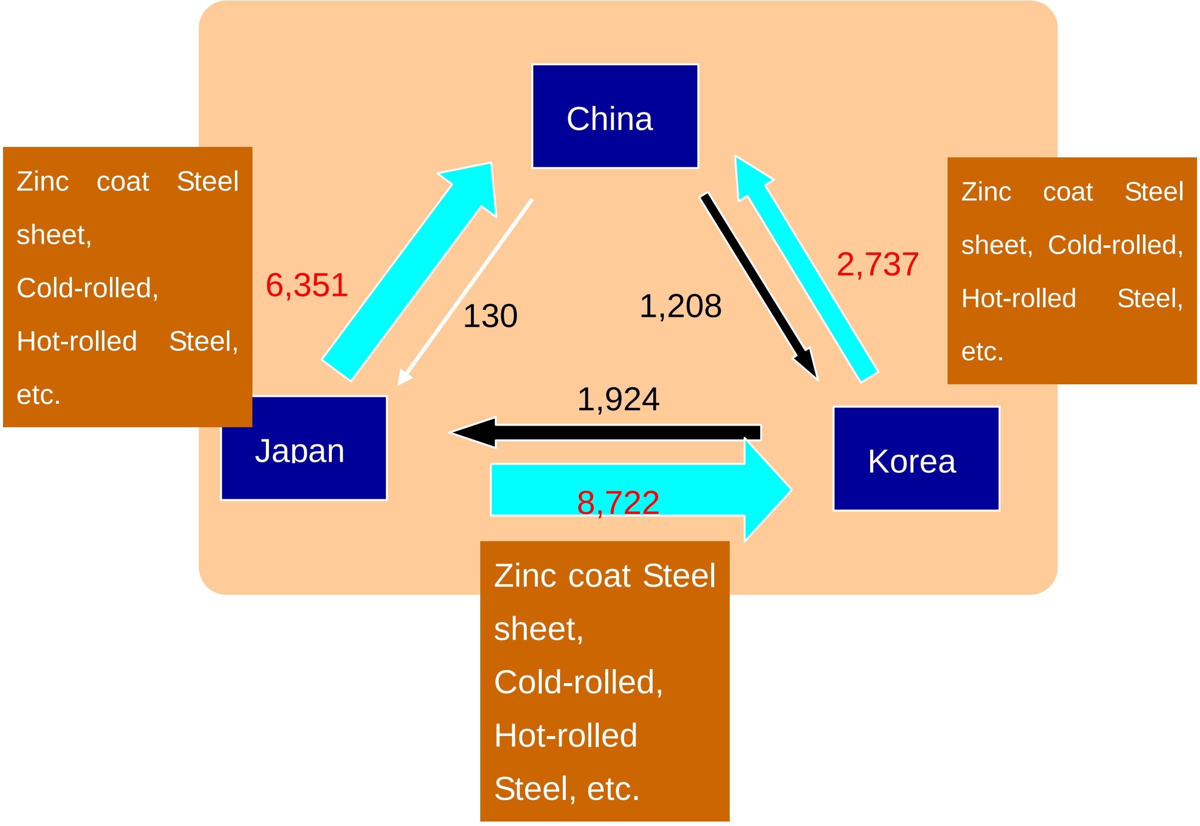
Table 3 Patent Application Concerning the Automotive Steel Sheet (Year 2000)

Application Content	Japan	Korea	US	Germany	France	UK
Steel Making	513	34	73	21	30	29
Hot Rolled Steel	351	35	41	28	24	26
Cold Rolled Steel	752	51	98	62	58	50
Surface Treatment Steel	445	37	54	24	30	24
Stainless	84	12	17	10	10	9
Steel Bar	90	4	11	5	2	6
Steel Pipe	19	2	4	3	3	3
Electrical Steel	282	28	48	21	20	18
others	190	6	33	8	3	3
Total	2726	209	379	182	180	168

Source: Hanazawa Toshitake (2005). "The evolution of the automotive steel sheet's manufacturing and function". JFE Corporation.

Since steel accounts for 70 percent of motor vehicle's weight and is used for producing more than 100 categories of auto parts, it remains the dominant material for automobile and its consumption trends are greatly impacted by auto industry. As the burgeoning auto market of China and the ambitious global expansion of Korean and Japanese automakers increase the auto production up to nearly 20 million units in the East Asian region, approximately one-third of the world total, demands for automotive steel products are surging as well. Meanwhile, the keen competition among automakers to improve fuel efficiency, safety and cost performance of vehicles also calls for the great endeavor of steelmakers to meet the technical and economical requirements. It is under such environment that steelmakers of Korea, China and Japan have established joint ventures and strategic alliance to serve their customers. For example, POSCO and Nippon Steel, Hyundai HYSCO and JFE entered into comprehensive alliance to produce automotive steel sheets in 2000; BaoSteel and Nippon Steel, Guangzhou Steel and JFE established joint ventures in China in 2003 to manufacture the products used for outer panels of auto. Trade figures also reflect that Japanese steel makers still maintain the net exporter of the high value added products while China is the net importer of automotive steel sheets in the region (see Figure 2). Nevertheless, when looking at the details of steel sheet procurement of automakers, we can see that some Japanese automakers also imported from POSCO the products for producing body parts other than outer panels. So even when we go down the category tree of steel products to the ramification of automotive steel sheets, there is still a rich variety according to the application areas of auto body which interestingly reflects the comparative competitiveness of companies in East Asia.

Figure 2 Trade Pattern of Steel Products among Korea, China and Japan (Million tons)



Practically, auto body parts are classified into four groups. (1) Exposed parts or outer panels such as roof, front fender, side panel outer, door outer, hood outer, etc. ; (2) Unexposed parts or inner panels such as floor, wheel house inner, door inner, dash panel, front pillar inner, center pillar inner, etc. ; (3) Reinforcement parts or structural parts such as front and rear side members, front and rear cross members, bumper reinforcement, door impact beam, etc,; and (4) underbody parts such as suspension member, suspension arm and accelerator housing (see Figure 3). To implement their specified functions optimally, parts in different area require the steel materials with different properties and characteristics. For instance, outer panels require rigidity, dent and corrosion resistance, inner panels also need fatigue and crash strength besides rigidity, and reinforcement parts are expected to absorb crash energy to secure passenger's safety. In addition, the overall vehicle's weight is required to be reduced to achieve better fuel efficiency while manufacturability like formability, weldability and paintability has to be improved. The solutions provided by steelmakers to meet these requirements are high strength steels, surface-treated panels and other innovative high-end products. The high strength steel can make the sheets thinner without compromising on safety standard and includes products such as bake hardenable (BH) steel, dual-phase (DP) steel, low alloy transformation induced plasticity (TRIP) steel and ultra-high strength steel (UHSS) with a wide range of strength from 340Mpa to over 1000Mpa to be applied to different areas.[1] Surface-treated steel, mainly refers to galvannealed (GA) steel sheets and non-alloy hot-dip galvanized (GI) sheets,

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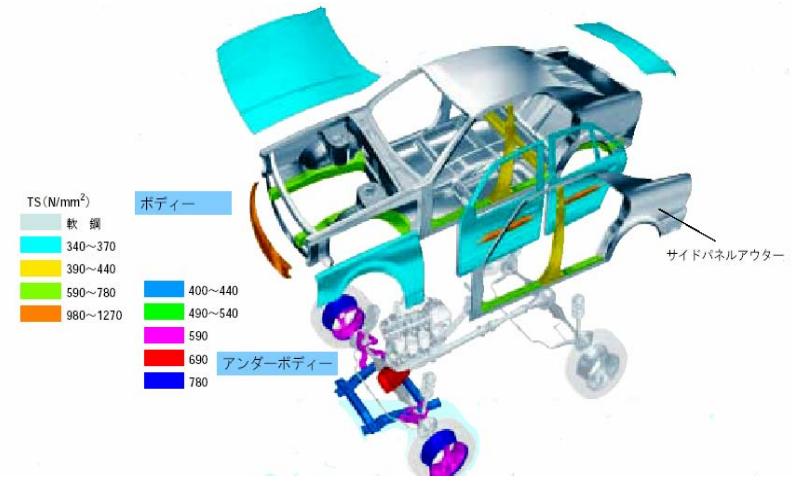
[1] Bake hardenable (BH) steel is being used for exposed parts, dual-phase (DP) steel and low alloy transformation induced plasticity (TRIP) are desirable for crashworthy parts, ultra-high strength steel (UHSS) with the tensile strength of 980 MPa or more is applied to bumper reinforcement and center pillars and high strength steel sheets are considered to be suitable for chassis.

can achieve excellent surface quality and formability by coating steel sheets with ZINC.

Figure 3 Variety of Steel Sheets for the Automotive Applications



Outer panels	Door outer, roof, front fender, side panel outer, etc.
Inner panels	Door inner, roof side inner, side sill inner, floor, wheel house inner, etc.
Structural parts	Front/rear side member, front/rear cross member, sheet rail frame, bumper reinforcement, door impact beam, etc.
Underbody parts	Suspension member, suspension arm, disc wheel, etc.

Japanese steelmakers have been maintaining the competitive advantages in producing these kinds of high end specialty products for more than twenty years, while Posco is still in the catch-up stage even though its net profit margin doubles that of the Japanese makers from making the relatively general-purposed products such as hot-rolled and cold-rolled sheets. How to explain such horizontal specialization between companies of different nations? In the following, we will present a framework of process architecture that describing the manufacturing features in making steel products for different automotive applications. The foundation of specialization is then proposed as the matching of process architecture and the organizational capability accumulated by the companies. Two cases of steel sheets --- bake hardenable (BH) sheet and surface-treated sheet that are especially for outer panels of automobile, are addressed in depth to illustrate our proposition.

2 Framework: Process Architecture and Organizational Capability

Process architecture is our newly coined concept to reflect the interdependence among different phases of non-assembled product's manufacturing, which is derived by analogy from the literatures on product architecture. Product architecture, one of the fundamental concepts in the field of engineering design, has recently been spotlighted in management science. Defined as "the scheme by which the function of a product is allocated to physical components and by which the components interact" (Ulrich, 1995, p.420), it provides a new perspective to examine the division of labor and coordination pattern within and between firms, or between nations (Langlois and Robertson, 1992; Baldwin and Clark, 2000; Fujimoto, Takeishi and Aoshima, 2001; Aoki and Ando, 2002). Reflecting the general design process, three elements are included in product architecture. First, functional requirements of the product to be designed are arranged in a structure (often in a hierarchical manner). Second, the means of achieving these functional elements are exploited by designing the visible physical building blocks. To put it in the former terminology, this is the process of mapping from function structure to physical components (Ulrich, 1995). Third, interfaces among interacting physical building blocks are specified (Ulrich and Eppinger, 1995). Modular and integral architecture are two extreme categories to make more concrete image of the concept. While modular architecture features in one-to-one function-component mapping and the de-coupled interface between components, integral architecture has components that interact with each other to fulfill the required functions.

Literatures on product architecture obviously focus on the assembled products with parts or building blocks combined to make a whole system. However, products of process industries do not have such decomposable feature and are generally made by using large amounts of heat and energy to physically and chemically transform materials. Therefore, instead of mapping functional elements to physical building blocks, product in process industries is the mapping from functional requirements to a multi-phase processing flow in which materials, equipment (machines) and working methods (man) coordinate to achieve the target processing parameters. In the same vein, the concept of interface in the case of the non-assembled products mainly refers to the interactions of parameters that are to be controlled between different phases. Process architecture, then, can be defined as the scheme by which the function of a non-assembled product is allocated to the parameters to be controlled in a serious of processing phases and by which these parameters of different phases interact. Taxonomy of process architecture is possible as well. A typical modular process architecture is the one in which the required function can be realized by a process flow with each phase's parameters independent. By contrast, under the integral process architecture, one required function has to be achieved through adjusting parameters of different phases.

Process architecture can be further represented in hierarchical diagrams and in matrix. Since process architecture focuses on the flow of transforming materials that is closed to a horizontal direction, matrix is considered as a better way for depicting both the mapping relationship between functional requirements and processing parameters, and the interactions among parameters of different processing phases (Fujimoto, 2003). Table 4 gives a conceptual representation of such matrix. The top horizontal column shows the required functions, while the vertical ones are stages of a processing flow. The cells of such a function-processing matrix are to show the mapping relationship between the required functions and processing stages. By simply aggregating the numbers of cells indicating that the meaningful mappings exist, and then dividing it by the total numbers of cells, we can get an index showing the integrity of processing coordination. It is called integral architecture index here.

Table 4 Conceptual Matrix of Function-Processing flow's Mapping

Process Function	F1	F2	F3	…….	Fm
P1	○		○		
P2		○			
P3	○				
…….				○Xij*	
Pn					○Xnm*

Integral Architecture Index = $\sum Xij^* / \sum_{i=1\sim n} \sum_{j=1\sim m} (Xij)$

The above formularization of process architecture can facilitate the analysis on the competence of companies in process industries. Corresponding to the elements in process architecture, the organizational capabilities of companies can be decomposed into several observable indicators such as the capability of translating functional requirements into the chemical composition of materials, the capability of translating functional requirements into the parameters for control, the capability of allocating parameters to appropriate processing phase and the capability of managing the parameters across the process. Process architecture is also a strategic variable for companies to choose. When the architecture is different, the path by which companies accumulate their organizational capabilities is likely to vary. It is in this sense that we propose in this paper that different process architecture of steel sheets for different applications of auto-body is one of the important factor to determine the comparative advantages of steelmakers in East Asia. In next section, after description of the general process of steel making, cases of bake hardenable and surface-treated steel sheets are addressed to show the relationship between process architecture and organizational capability.

3 Case Study: steels for outer panels of automobile

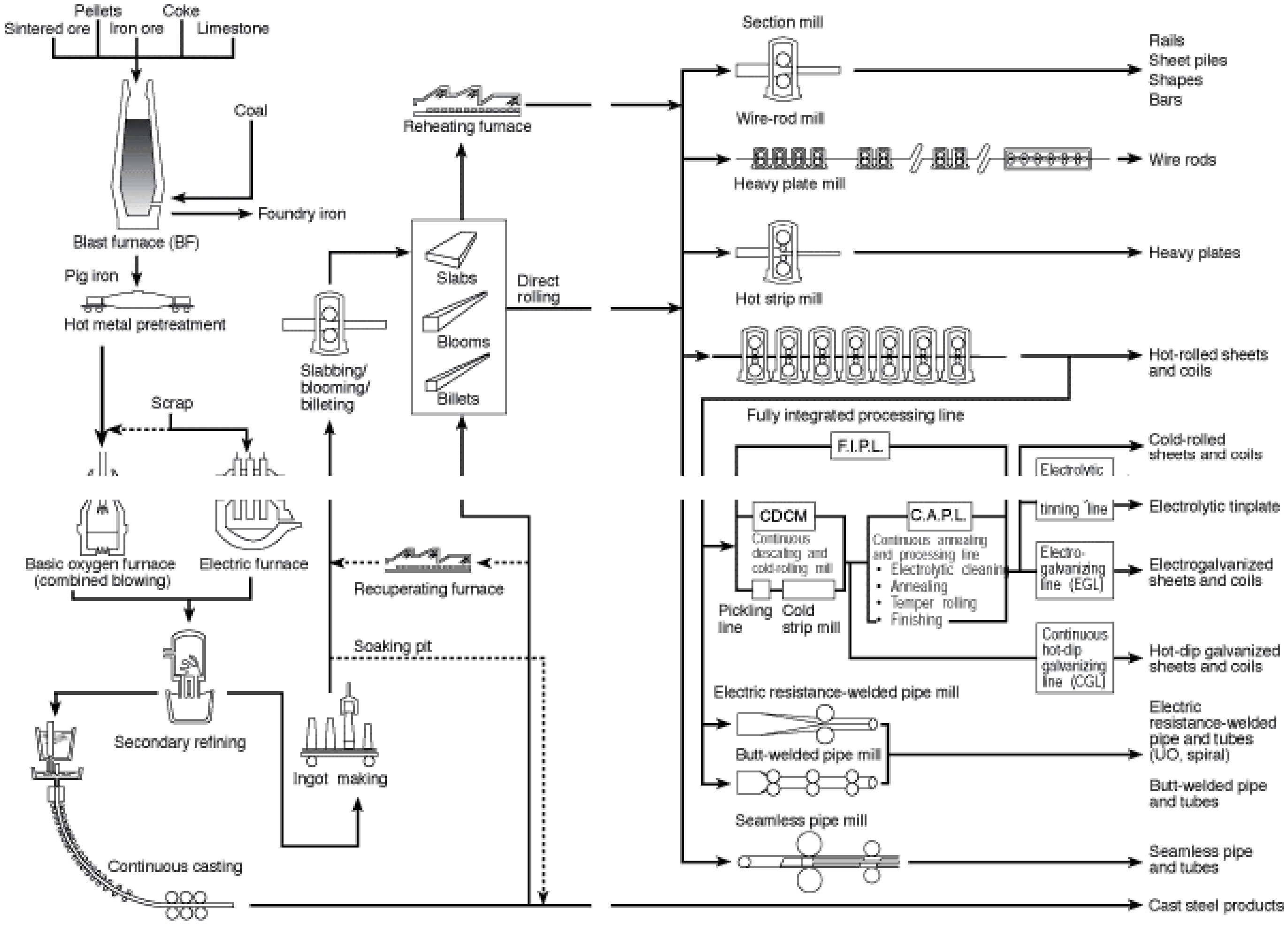
3.1 General process of steel making:

The general process of steel making is consisted of a series of phases such as iron making, steel making and hot rolling, and will go further to include cold rolling, annealing or hot dip zinc coating to produce flat steel products like automotive sheets where advanced requirements are to be met. See Figure 4 for the general steel making process.

During iron making process, raw materials (iron core, coal and limestone) are put into blast furnace where hot air is pumped to melt them. Pig iron, the output of this processing, contains high carbon contents that make the material too brittle and has to be refined.

The subsequent steel making phase consisting of converter, secondary refining and continuous casting processes then is for further removal of carbons and other impurities. At first, scrap steel is charged into the converter followed by liquid iron from the blast furnace. The oxygen blown in will combine with carbon and other unwanted elements through oxidation reaction. The chemical composition of materials for different applications is also adjusted here by adding alloys.

Figure 4 General Steel Processing Flow



Source: Nippon Steel Corporation’s website.

In the secondary refining, the molten steel is tapped from the converter to a vacuum degasser where hydrogen, atmospheric and volatile impurities are further removed. It is of vital importance for high grade steel making such as for automotive use where ultra-low level of carbon contents is required. In the continuous casting process, molten steel is poured into a reservoir at the top of the casing machine. Then it passes at a controlled rate into a water cooled mould where the outer shell of steel becomes solidified. At the end of the machine, the solidified steel is straightened and cut to the required length. Among these semi-finished products like slabs, blooms or billets, slabs are used for flat-rolled products.

In the following hot rolling mills, slabs are first reheated around 1400 degree. Then they go to a roughing stand to be formed in the shapes and dimensions closed to the requirements. After that, the slab passes continuously through a series of finishing stands which progressively squeeze the steel to make it thinner and longer. Finally the long strip of steel is coiled and cooled. In the cooling process, the cooling speed will affect the mechanical properties of the steel and thus needs accurate control.

After hot rolling, further processing is conducted to reduce thickness and improve performance characteristics of steel products for high end uses. In cold rolling, the steel stripe is first uncoiled and then passes through a series of rolling mill stands that reduce its thickness to below1mm. Since cold rolling significantly increases material's hardness, the strip is subsequently annealed (raising the temperature and then slowly cooled) to improve ductility since a recrystallized structure is induced in the steel. The introduction of the continuous annealing line (CAL) by Japanese steelmakers in 1970s remarkably improves the productivity through continuous conduction of cleaning, annealing and adjustment rolling. Compared with the batch annealing, CAL reduces lead time from 3 days to 5-10 minutes.

Finally, there are various types of coating processes to achieve functions of corrosion resistance and improved manufacturability for end users. In the case of zinc coating that is usually applied to automotive sheets, several processing methods are available. One is to use electricity to make the zinc settle on the metal in the electrolysis bath. Such electrolytical galvanization uses cold rolled strip after continuous annealing and its output is abbreviated as EG. Another way of zinc coating is to submerge ("hot dip" in formal terminology) the cold rolled strip without being annealed in a bath of molten zinc. As the steel emerges various means are used to level and control the thickness of the zinc coating. The product of such processing is called GI. When the steel is subjected to an additional annealing step, the result is a completely alloyed iron-zinc coating which is called GA. Exhibiting both high corrosion resisting attributes and cost performance, hot dip zinc coating, especially GA is becoming the mainstream product for outer panels of automobile in Japan.

The above general process has been a dominant design in steel industry. Therefore, products for different applications are manufactured through the design of chemical composites and processing parameters to be controlled in each step. When functional and quality requirements from end users such as automaker become multidimensional and rigorous, the increasing complexity in the process inevitably gives rise to interactions between upstream and downstream and calls for the integrative capability of steelmakers. The following two cases are the examples to show the comparative advantages of Japanese makers in this respect.

3.2 Bake hardenable (BH) steel:

The outer panels of automobile such as hoods, doors, deck lids and fenders require high resistance to denting due to stone damages or palm printing in the final assembly, their complicated shapes also require materials to have good formability for processing methods like deep drawing or stretching. Such multiple functional requirements seem to pose a tradeoff problem: while dent resistance calls for high yield strength, high surface quality against distortion in press forming needs the yield strength below 240 MPa (Takahashi, 2003). Although dent resistance is a function of both yield strength and thickness, competence on vehicle's weight reduction to improve fuel efficiency eliminates the latter choice while turning to high strength materials for solution. Bake hardenable (BH) steel is considered ideal to satisfy all these requirements by exhibiting the features that it remains "soft" (low yield strength) prior to manufacturing but becomes "hard" (high yield strength) after press stamping and paint baking operations. Invented by Japanese steel makers in early 1980s, BH steel has been adopted by automakers worldwide.

The mechanism behind the characteristics of BH steel to meet conflicting requirements not simultaneously but sequentially actually utilizes a phenomenon in metallurgy known as strain aging, which reflects the interactions between carbon atoms and dislocations in ferrous crystalline structure. A dislocation is simply a defect in grid-like crystalline structure (lattice) in which some atoms are missing in a layer. The structural instability of dislocation makes it easy to move when receiving external forces. This movement does not affect the vast majority of atoms and does not require large scale movement of the layers in the structure. It is this movement of dislocations that transform metal material's shapes. The easier the dislocations' movements, the more malleable and ductile the material is. On the other hand, when dislocations in ferrous crystalline structure have difficulty in moving, the steel material becomes stiff and hard. One Factor that hinders dislocation movements is the accumulation of dislocations during transformation by external forces. When the number (or density) of dislocations increases, there is high possibility that they interact and entangle with each other which locks the further movement of dislocations. Another factor is that carbon and/or nitrogen atoms tend to gather around dislocations and bury the missing places under the conditions like high temperature and duration of time, which will result in the stabilization of the crystal structure. The strain aging phenomenon refers to such locking of dislocations. Therefore, the BH effect can be achieved by maintaining an appropriate level of carbon and/or nitrogen ingredients in steel that do not stabilize the dislocations before stamping, but diffuse towards dislocations during baking in the paint shop as dislocation's density also increases after stamping formation as well. Too low level of carbon solute will decrease the BH effect and the excess amounts of it will make the steel sheet hard under room temperature. This so-called room-temperature aging is likely to make steel sheets broken during stamping.

In practice, about 0.001 percent (10 ppm) of solute carbon is maintained for producing BH steel sheet. However, during the annealing process, even minute level of solute carbon tends to deteriorate the formability for deep drawing. As one alternative to solve this trade-off problem, niobium (Nb) is added to extract carbon in the compound form as niobium carbide (NbC) before annealing. The Nb/C atomic ratio, then becomes another crucial parameter to control since it is closely related to annealing temperature, bake-hardenability and formability of steel material.[2] It has been shown that controlling the atomic ratio about 1.0 and maintaining the annealing temperature above 850 degree can achieve both high level of formability and bake-hardenability (Sato et al., 1991)[3].

So the processing of BH steel begins with the ultra-low-carbon steel material with Nb/C ratio around 1.0, then goes through hot rolling mill over 600 degree where carbon and nitrogen are extracted in the compounds NbC and AIN. After cold rolling and heating above 750 degree, the steel sheet will have a recrystallization texture with NbC and AIN stable around this temperature. But

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[2] The Nb/C atomic ratio has a positive relationship with annealing temperature. When annealing temperature holds constant, the lower the Nb/C ratio is, the lower the BH effect achieved.

[3] The following description is based on the materials from JFE Corporation and the data is just for reference.

when the temperature continues to go up to higher than 850 degree, NbC will dissolve so that solute carbon is acquired. Since the steel's texture has been stable on such temperature level, solute carbon will not make ill impact on it. In addition, AIN is also stable due to its higher resolution temperature over 900 degree. Finally, to leave solute carbon in the product, the crucial step is the rapid cooling of steel stripe with the average speed around 40 degree per second. Cooling down slowly will make solute carbon combine with niobium again.

Put in the terms of process architecture, the manufacturing of BH steel can be summarized as follows. First, the means of satisfying conflicting functions of high dent resistance and good formability are translated into the utilization of strain aging mechanism, and then are further translated into the acquirement of a proper amount of solute carbon in the steel material. Second, parameters to achieve the optimal amount of solute carbon are allocated to the phases of the whole processing flow. The upstream vacuum degasser in secondary refining can realize carbon contents as low as 10 ppm, but such direct method doesn't satisfy the quality requirements of the downstream annealing process. To solve this problem, additives such as niobium are added in the upstream to combine with carbon atoms before annealing. The Nb/C atomic ratio has a positive relationship with annealing temperature. Furthermore, when annealing temperature holds constant, the lower the Nb/C ratio is, the lower the BH effect achieved. On the basis of these principles that form a closed cause-effect loop, the Nb/C ratio, temperature of hot rolling and annealing, and the speed of cooling in annealing process have to be controlled precisely. Therefore, the interactions among these parameters across different phases of processing make us to say that the process architecture of BH steel is an integral one.

Using function-process matrix, we can measure the architectural attributes of BH steel processing as Table 5 shows. The judgments of the mapping relationships in this paper were conducted by one engineer from a Japanese steel company who has long-year experience in designing automotive steel sheets.

Table 5 Bake-hardenable (BH) Cold Rolled Steel Sheet for Automobile's Outer Panel

Function Process	Surface Appearance	Corrosion Resistence	Dent Resistence	Formability	Weldability	Paintability	Dimen Sional Accuracy	Rigidity
Iron Making								
Converter	○	○	○	○	○			
Secondary refining	○	○	○	○	○			
Continuous casting	○			○				
Hot Rolling	○			○				
Pickling	○							
Cold Rolling	○		○	○			○	○
Continuous Annealing	○		○	○	○	○	○	

The integral architectural index is 0.41 (=26÷(8X8)), which can be viewed as relatively integral.

Although invented two decades ago and haven been introduced by many other makers so far, the BH steel production is still a competitive field of Japanese makers. Besides higher yield rates which contribute to cost competence, Japanese makers especially have expertise in making the products with less aging effect. Because carbon atoms remaining in a steel sheet tend to diffuse to dislocations in ferrous crystal, the steel sheet will become hard (aging) even under room temperature when being stored after a certain period of time. The know how of Japanese makers in integrating the processes can prevent the materials from aging for three months, which is long enough for satisfying the oversea demands.

3.3 Surface treated steel: the case of galvannealed product (GA)

Surface treatment, as introduced in the general process of steel making, is to coat zinc on both sides of steel stripes after cold rolling process. Corrosion resistance is one of its main functions because zinc can protect the base steel by providing a barrier to corrosion elements and also by the sacrificial nature of the coating[4]. The surface treated steels are especially suitable for outer panels of automobile where not only corrosion resistance, but also aesthetic appearance are required. In Japan, the hot dip galvanneal coating through which GA steel is produced has been a mainstream[5]. It is the process that after a steel strip exits the coating bath, an in-line heat treatment is conducted to convert the molten zinc coating to a zinc-iron alloy as iron diffuse from the steel into the coating at high temperature.

Because corrosion resistance is proportional to the coating thickness, the heavier coating on the steel will result in better durability in corrosive atmospheric environment. The technology of just conducting heavy coating is not very difficult, what is demanding is that automakers require more functions such as formability, weldability and paintability for convenient application. With the zinc-iron alloy surface that is actually harder than the base steel, GA can improve spot weldability because the coating's high electrical resistance, along with higher hardness and higher melting point allow good welds to be obtained at lower currents. Another primary attribute of GA is the improved

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[4] The corrosion rate of zinc is considerably below that of ferrous materials in the air, so zinc can provide a barrier between steel and external environment. The sacrificial nature of zinc coating lies in the fact that zinc will preferentially corrode to protect steel against rusting when the coating is damaged.

[5] That GA becomes the mainstream product in Japan does not mean it has the best material properties than GI or EG. It is just a satisfactory solution subject to the manufacturing constraints (such as economic and environmental considerations) in Japan.

coating adhesion and ease of painting. The dull gray appearance of GA’s surface can accept paint readily; furthermore, performance of GA under paint can be synergistically improved because of the good compatibility between the alloy surface and the paint. The hardness of the alloy surface also provides resistance to scratches during handling and other manufacturing damages. Nevertheless, the hard and relatively brittle alloy surface of GA will pose problems for good formability. When formed into intricate shapes by deep drawing, the coat will come off the base steel as a result of compressive strain. The frictional resistance between coating and die cause this powdering phenomenon. The heavier the coating, the more powdering will exhibit. So the similar trade-off situation emerges again as shown in the case of BH steel.

To strike a balance between coating adhesion and formability, optimal control of alloying reaction is called for. Since the iron in the steel diffuse into zinc to make crystals of the alloy under high temperature, the concentration of iron is high where close to the base steel and is low where near the coat surface. Under the situation of insufficient heating, the concentration of iron is too low in the alloy which will result in great frictional resistance between coating and die (the flake phenomenon). In contrast, excessive heating will cause the iron concentration too high and the coating so brittle that the powdering phenomenon occurs. By the way, if the hot dip zinc coating is continuously heated, it will reach the steady state with 98% iron and 2% zinc. When making the proper alloy, the process should be stopped far earlier than reaching the steady state. Therefore, the control of time and thermal conditions (heating temperature and speed) is crucial in arriving at an optimal proportion of iron and zinc in the alloy coating.

Besides the heating conditions control, the alloying reaction also depends upon the chemical composition of steel and the density of aluminum in the coat bath for controlling the reacting timing of iron and zinc. As the function of GA steel will differ significantly when such conditions change, the parameters not only in the process of hot dip coating and reheating, but also in the upstream phases of steel making and hot rolling where the material's features are adjusted.

The more complicated case is to produce the galvannealed steel with bake hardenability. Beyond the problem solving loop with interactive parameters for making the BH steel, additional functions provided by GA further extend the processing flow and add new parameters for control. Since the BH effect depends upon the amount of solute carbon in the steel, the efficient way to make BH-GA steel is to maintain the acquired solute carbon from reacting with niobium and iron during the further reheat treatment in the continuous galvannealing line. The precise thermal control is vital again in this process. It has been shown that after rapid cooling from around 850 degree to 450 degree, the steel stripe reheated to 400-600 degree for zinc-iron alloy formation will have little change in solute carbon. Contrarily, the BH effect will deteriorate when the material is cooled down to 750 degree or to 300 degree (Sato, et al., 1991). In addition, to prevent ferrous atoms combine with dissolved carbon, rapid cooling from 500 degree to 200 degree is once again essential after the alloying reaction.

The process architecture of GA steel, therefore, is similar to that of BH product in that the multi-dimension functional requirements inevitably incur the trade-off constraints and an integrative approach that coordinates the upstream and downstream of the process flow becomes essential. Especially when GA is applied to outer panels of automobile, it is subject more to the sensual evaluation of customers in the sense that attributes such as aesthetical appearance cannot be definitely depicted in technology standard. This tacit nature of evaluation, together with the integrative manufacturing know how, can be considered as the pivotal force to sustain the competitive advantage of Japanese steelmakers for more than two decades.

The architectural attribute of surface-treated steel sheet, as Table 6 shows, is also a relatively integral one.

Table 6 Surface Treatment Steel for Automobile's Outer Panel

Function Process	Surface Appearance	Corrosion Resistence	Dent Resistence	Formability	Weld ability	Paint ability	Dimensional Accuracy	Rigidity
Iron Making								
Converter	○	○	○	○	○			
Secondary refining	○	○	○	○	○			
Continuous casting	○			○				
Hot Rolling	○			○				
Pickling	○							
Cold Rolling	○		○	○			○	○
Continuous Annealing	○		○	○	○	○	○	
Continuous Galvannealing	○	○	○	○	○	○	○	

The integral architectural index is about 0.48 (= 33 ÷(9X8)).

3.4 Discussion:

The bake hardenable and galvannealed steel products are two illustrative examples to show the features of integral process architecture. We can see that multiple functional requirements from customers (automakers) increase the complexity of the processing flow in that the parameters and their interactions to be controlled multiply. The enhanced complexity then calls for sophisticated capability of coordination and integration during steelmaking, where the know how such as the thermal control of fluid moving in high speed, the mechanical control of rolling and the stable quality assurance during continuous twenty four hour operation has to be accumulated over a long period of time. Embedded in the organizational context, a great amount of the know-how also bears the tacit feature. Japanese steelmakers are successful in accumulating such organizational capabilities of integration through the practices of life long employment, on the job training and temporary job rotation. Their competitive advantage in making high end products like BH and GA steel, as shown in our case study, indicates that the complicated causal linkages in the integral process architecture and the tacit nature of production know how tend to create a great barrier to imitation and technology transfer. It is also compatible with our proposition that the matching of organizational capability and process architecture will significantly influence the competitiveness of a firm.

This point can be further clarified by concisely examining the capability disparity of Posco. Although Posco has been the most profitable steelmaker via mass producing the general purpose products, it is still in the catch-up stage of manufacturing high end ones. More interesting is that the construction of Pohang plant during 1970s was under a turnkey contact with Japan Group (mainly formed by Nippon Steel Corporation and NKK). Not only was the plant’s hardware the clone of the most advanced one of the Japanese makers, but also the Japanese style of management was introduced. Similar is the second plant of Posco, Gwangyang that was also equipped with the ultra-modern machinery from Japan and Europe and was laid out along the coast as most Japanese plants do. Then the question arises that with the initial condition quite close to the Japanese way, how

Posco took a different path of development?

The reason lied in the nature of process architecture and the positioning strategy of Posco. Putting equipment utilization as the primary target, the company chose to concentrate on producing general purposed products to serve the demands from shipbuilding and construction industries. Because the functional requirements of these applications are not as complicated and strict as those for automotive outer panels, the solutions can be acquired on the basis of routine principles. Moreover, quality improvement of the products can be achieved through the accuracy enhancement in certain phase of processing without coordinating with other steps. That the introduction of vacuum degasser can revolutionarily purify steel materials and reduce carbon contents to less than 20ppm level is one example. The dimensional accuracy of products can be improved by upgrading rolling technology is another. The advancement of digital control technology also facilitates this kind of capability building. Put in our terminology, such quality improvement through pinpoint upgrading can be viewed as the feature of modular process architecture. As the results, Posco has achieved the most efficient production and amazing cost competitiveness by selecting the necessary items to realize the scale economy. While it can produce the automotive sheets for certain application areas and for certain segment of products where functional requirements are not so strict or the cost performance is more emphasized, on the other hand, it has not accumulated the organizational capabilities competitive enough in making the high end ones applied to the outer panels of the cars for export.

In order to make a comparison, we also have the architectural attributes of cold-rolled steel (which is one of the main products of Posco for domestic and export uses) measured by our correspondent. See Table7 for the architectural features of cold-rolled steel.

Table 7 Cold Rolled Steel for Inner Panels of Automobile

Function Process	Surface Appearance	Corrosion Resistance	Dent Resistance	Formability	Weld ability	Paint ability	Dimensional Accuracy	Rigidity
Iron Making								
Converter		○		○	○			
Secondary refining		○		○	○			
Continuous casting				○				
Hot Rolling				○				
Pickling					○			
Cold Rolling				○	○		○	○
Continuous Annealing				○			○	

The integral architecture index of cold-rolled steel is 0.23 (=15/(8X8)), which can be viewed as relatively modular.

In the case of Chinese steel industry, the path of capability building shares certain similarity with that of Korean makers. More than seventy percent of its steel products are for low end construction applications while automotive steel sheets depend severely upon import. The particular historic path and institutional environment also make special problems confront China such as extreme low concentration of the industry and the dispersed and irrational localization of companies.

Therefore, different positioning strategies of the companies in East Asia have lead to different paths of capability accumulation that match different process architectures required by products. This kind of specialization has also constructed a micro foundation so far for inter-firm technological collaboration and trade within the region.

As automobile market expands rapidly, both Korean and Chinese steelmakers have begun to strengthen their competitiveness in the high end segment tailored for automotive applications. Posco has listed the automotive steel as one of its big four strategic products. Bao steel corporation and Nippon steel corporation, Guangzhou steel corporation and JFE have also established joint ventures in China to make surface treated steels for automobile outer panels, which has the epoch-making meaning in that it is the first time for Japanese makers to provide the galvanized and galvannealed technologies to oversea companies. The dynamic development paths of the companies may show a convergent trend, but the effect of path dependence and the inherent logics of accumulating integrating organizational capabilities are likely to maintain the differentiation points among the steelmakers.

4 Conclusion:

After formularizing the concept of process architecture, we attempted to explain the horizontal division of labor in steel manufacturing for auto body applications in East Asia within our framework. The case study on specialty steel products of bake hardenable and surface treated steel sheets illustrates that Japanese makers have accumulated their organizational capabilities matching the requirements of integral processing architecture. On the other hand, Posco and some Chinese makers have focused on relatively general purpose products with more modular processing architecture as the ultra-modern equipment introduced can upgrade the element technological capabilities within relative short term. The differences in process architecture and the path of accumulating organizational capabilities therefore influence the different positioning of the companies in the Ease Asian region.

The recent entry of Posco and Chinese makers into the high end segment indicates that the development path of companies may converge as the scope of products gradually overlaps. Meanwhile, global procurement by automakers also exerts stronger competition pressures among steelmakers. Nevertheless, the robust growth and the amazing variety in the demands for automotive applications can still provide the space for inter-firm cooperation and for differentiate positioning. As long as companies specialize in the sector with comparative advantage, mutual growth and improvement can be achieved. When we were examining the limited subject of automotive steel sheet from the perspective of process architecture, the bright and beautiful picture drawn by David Ricardo almost 200 years ago emerged in our minds again.

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