論文 / 著書情報
Article / Book Information

Title	Influence of Understanding of Physical Phenomena in Materials on Supply Chain Patterns of Steel Products
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Journal/Book name	ISIJ International, Vol. 60, Issue 9, Page 2112-2117
Issue date	2020, 9
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ISIJ International, Vol. 60 (2020), No. 9, pp. 2112–2117

Influence of Understanding of Physical Phenomena in Materials on Supply Chain Patterns of Steel Products

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(*Received on January 20, 2020; accepted on March 13, 2020; J-STAGE Advance published date: May 9, 2020*)

In this study, supply chain patterns of steel products are investigated from the viewpoints of quality assurance responsibility and understanding of physical phenomena in steel. This study focuses on the differences in supply chain patterns between steel nails for common use and valve springs for the automotive industry. In the supply chain of steel nails for common use, which takes a conventional pattern from raw materials to final products, the quality of each supplier's product is guaranteed just by the Japanese Industrial Standards (JIS), and no supplier takes quality assurance responsibilities beyond its business range. By contrast, in the supply chain of valve springs for automotive use, each supplier takes quality assurance responsibilities for the final product beyond its business range, and the suppliers cooperate with one another to fulfill stringent quality requirements by automotive manufacturers. Therefore, the supply chain pattern of valve springs is different from the conventional pattern of common use steel products like steel nails. It was also found that the supply chain pattern of valve springs can be caused by the insufficient understanding of physical phenomena in steel, martensitic transformation and hardening in this case. This study suggests that the conditions that determine the supply chain pattern of a steel product could be business practices for quality assurance, namely based on standard specifications or users' requirements, and the natural scientific understanding level about physical phenomena in steel. Although this study focuses on steel nails and valve springs, this finding is applicable to other steel products.

KEY WORDS: supply chain; interfirm cooperation; steel nail; valve spring; quality assurance; martensite.

1. Introduction

A supply chain is defined as the entire process of making and selling products, including every stage from the supply of materials and manufacturing of the products to their distribution and sale.[1)] The conventional supply chain pattern is shown in **Fig. 1**, where A, B, and C are suppliers, and D is the consumer of the product.

In this conventional supply chain pattern, semi-finished products are traded sequentially from the upstream product suppliers A and B to the final product supplier C, and the quality of each product is guaranteed within each business range. That is, each supplier completes its own quality assurance responsibility for its products within its business range, and the business range of each company is the same as the range of quality assurance responsibility.

According to Nishio,[4)] a supply chain of steel nails takes the conventional supply chain pattern as shown in Fig. 1, where A is a supplier of steel wire rods (hereinafter referred to as wire rods) which are raw materials of steel nails, and B is a supplier of drawn wires for C which is a steel nail manufacturer. It is known that in the steel nail supply chain, the interfirm cooperation between suppliers is sparse and that one supplier could easily be replaced by another supplier. In this pattern, the quality assurance responsibilities for each supplier's product are completed within the company's business range.

By contrast, the supply chain pattern of valve springs appears to be different from that of steel nails. According to Nishio and Fujimura,[5)] the cooperation between suppliers mainly takes place in the following three situations in order to guarantee the final product quality of valve springs:

- New product development and to obtain automotive manufacturer's approval for the production process
- To obtain the revised approval in the case that some of the suppliers' manufacturing conditions for an already approved final product were changed
- To investigate the cause and countermeasures by suppliers when some failures are found after the valve spring delivery (This business custom for quality assurance is called "performance guarantee" by Kawabata[6)] and Nishio and Fujimura.[5)])

The range of cooperation to ensure final product quality in these three cases is represented by the dotted line in **Fig. 2**.[5)] In Fig. 2, A is a wire rods manufacturer for B, and B

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DOI: https://doi.org/10.2355/isijinternational.ISIJINT-2020-033

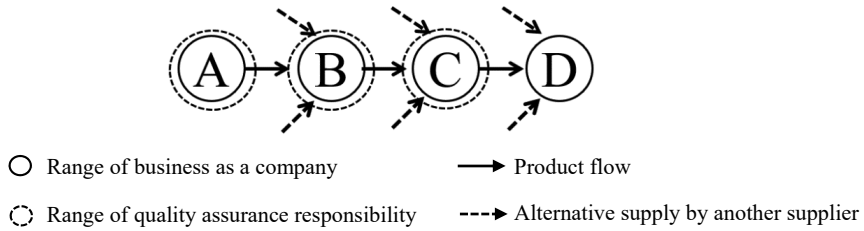

Fig. 1. Conventional supply chain pattern.[2,3] A, B, and C are suppliers, and D is the consumer of the product. The range of each supplier's quality assurance responsibilities is the same as the business range of each supplier.

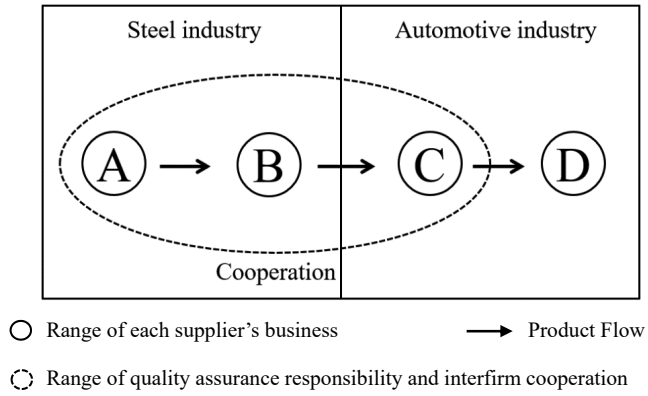

Fig. 2. Valve spring supply chain pattern.[5] A is a steel manufacturer and B is a secondary processor. A and B are in the steel industry. C is a valve spring manufacturer and D is an automotive manufacturer. C and D are in the automotive industry. A, B, and C are all responsible for the quality of the final product for D.

is a secondary processor which supplies oil tempered wires (hereinafter referred to as tempered wires) to C, a valve spring manufacturer. A and B belong to the steel industry, and C belongs to the automotive industry. It should be noted that the interfirm cooperation in the valve spring supply chain is formed across the boundaries of the steel and automotive industries, although neither special strategic management agreements nor capital policy partnerships are identified between the three valve spring suppliers.[5] In addition, existing suppliers A, B, and C are stable, and the suppliers in this supply chain are not easily replaced by other companies outside.[5] It is clear that the range of the quality assurance responsibility of each supplier is not the same as the range of each supplier's business. In terms of quality assurance responsibility, the supply chain pattern of valve springs is different from the conventional supply chain pattern.

In the light of the discussions in the previous studies above, the research objective of this study is to clarify the reason why the supply chain pattern of valve springs is different from the conventional pattern of steel nails. In order to clarify this difference, more detailed analyses of the supply chain patterns are required. Williamson[7] and Baldwin[8] maintain that the analysis of a production system requires technological and natural scientific perspectives. Accordingly, with respect to the supply chains in question, this study analyzes the following items to clarify the research objective:

(1) Differences in business practices for quality assurance between the supply chains (to be discussed in section 3)
(2) Influence of natural scientific understanding level about physical phenomena in steel (to be discussed in section 4)

2. Methods

This study cannot rely on experimental data, unlike the natural science studies. Therefore, the required data collection depends on the documents of previous studies and interviews. In this study, the document search provided information on steel nails and valve springs such as their manufacturing processes and physical phenomena found in product materials. The documents were collected mainly from ISIJ International and *Tetsu-to-Hagané*. JIS information was obtained from the Japanese Industrial Standards Committee (JISC).[9]

On the other hand, because this study covers both natural sciences and social sciences and the number of previous studies is limited, the information about behaviors of suppliers within the supply chains cannot be obtained from the document searches. Therefore, the data collection through questionnaire surveys or interviews are effective measures. However, since the number of surveyed companies are limited, quantitative statistical analysis by questionnaires is not appropriate. Therefore, this study is a qualitative study in which the interviews have been commonly adopted.[10–12] The interview as a research method was used in previous studies on steel or other materials as well.[13–16] The interviews for this study were performed from October 2015 to February 2020 with key persons in Japan, who are engaged in steel manufacturing, secondary processing, valve spring manufacturing, steel nail manufacturing, and research at universities. According to these methods, the analyses for the items (1) and (2) shown in section 1 are conducted from the next section.

3. Differences in Business Practices for Quality Assurance between Supply Chains

In this section, in order to achieve the research objective, this study compares the business practices for quality assurance between the supply chains of steel nails and valve springs.

To start with, this study reviewed the manufacturing process of steel nails. The steel nail, one of common use steel products, is defined as the product certified by JIS represented by JIS A 5508.[17] The information of the production process of steel nails was collected by the document surveys mainly from *Tetsu-to-Hagané*, and the information related

to JIS was acquired from JISC.[9)]

The following information was obtained from the approaches above. First, the major production processes of forming steel nails are drawing and forging.[18–20)] As seen in **Table 1**, low carbon steel wire rods[21)] (JIS G 3505), the raw material for steel nails, are produced by steel manufacturers and are drawn to be low carbon steel wires[22)] (JIS G 3532) by secondary processors. The steel wires are forged into steel nails[17)] (JIS A 5508) by nail manufacturers.[18–20)] Second, low carbon steel wire rods are specified in JIS by the shape and chemical composition,[21)] while low carbon steel wires are specified in JIS by the shape and mechanical properties.[22)] Third, there are many candidates of suppliers, which hold JIS mark certificates to produce low carbon steel wire rods, low carbon steel wires, and steel nails, as seen in Table 1.

In the case of steel nail supply chain, no interfirm cooperation between suppliers is reported.[4)] The interviews were conducted to know how the steel nail suppliers accomplish their quality assurance responsibilities. It was confirmed by the interviews with steel nail manufacturers that each supplier completes its own quality assurance responsibilities based on JIS for its own product in the range of its business and that there are many candidates of suppliers to enter the supply chain with JIS mark certificates. Therefore, the range of each company's business is the same as the range of its quality assurance responsibilities defined by JIS regulations and the steel nail supply chain takes the conventional pattern as shown in Fig. 1.

On the basis of the above discussions, **Fig. 3** shows the supply chain pattern of steel nails. The business practices for quality assurance of steel nails are based on JIS. Therefore, it is considered that many suppliers can be the candidates of suppliers to manufacture products conforming to JIS and that the conventional supply chain pattern shown in Fig. 1 emerges.

For the analyses of valve spring supply chains, the information of the production process of valve springs was collected by the document surveys mainly from a management journal and a steel manufacturing company's technical journal. According to the surveys, the raw materials are wire rods manufactured by steel manufacturers and the wire rods are drawn and heat-treated by secondary processors to be tempered wires with the necessary strength for valve springs.[23)] Tempered wires are processed by spring manufacturers to the valve springs to be delivered for automobile manufacturers.[5,23)] In the case of valve spring supply chain, JIS is not applied in practice as shown in Table 1. Valve springs are, so to speak, custom-order products with no JIS specification. Although there is a JIS for wire rods (piano wire rods)[24)] and for tempered wires (oil tempered wire for valve springs)[25)] as seen in Table 1, no secondary processors in the supply chain holds manufacturing certificates of JIS of tempered wires for valve spring business. This shows that it is impossible to realize the high-quality requirements of Japanese automotive manufacturers for valve springs by using the existing JIS quality level tempered wires. In order to confirm the quality level of raw materials of valve springs, the interviews were conducted with wire rods and tempered wire manufacturers. The interviews revealed that the quality requirements for wire rods and tempered wires are much higher than JIS G 3502[24)] and G 3561.[25)] Therefore, JIS is not used in this supply chain.

The information of the behaviors of suppliers in the valve spring supply chain was obtained by the interviews with wire rods, tempered wire, and valve spring manufacturers. According to the interviews, the three suppliers cooperate with one another and keep seeking out optimum manufacturing conditions through trial and error, to respond to the higher quality requirements of automotive manufacturers than JIS. **Figure 4** shows the supply chain of valve springs with the manufacturing process and the cooperation between suppliers. That is, the business practices for quality assur-

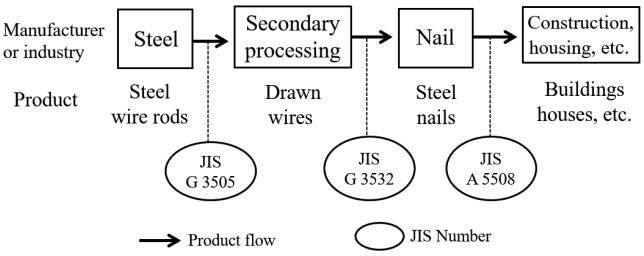

Fig. 3. Steel nail supply chain and JIS system.[4)] The supply chain takes the conventional supply chain pattern. Each JIS number is from JISC.[9)]

Table 1. Comparison of JIS between steel nail and valve spring. While the quality assurance in the steel nail supply chain is based on JIS regulations, JIS is not practically applied in the case of valve springs. The JIS numbers and the number of companies of JIS mark certificate holders are obtained from JISC.[9)]

Supply chain	JIS items	Suppliers		
		Steel manufacturer	Secondary processor	Final product manufacturer
Nail	Product	Low carbon steel wire rods	Low carbon steel wires	Nails
	JIS No.	G 3505	G 3532	A 5508
	Number of companies of JIS mark certificate holders	13	52	31
Valve spring	Product	Piano wire rods	Oil tempered wire for valve springs	Valve spring
	JIS No.	G 3502	G 3561	N/A
	Application of JIS	Not actually applied in practice		

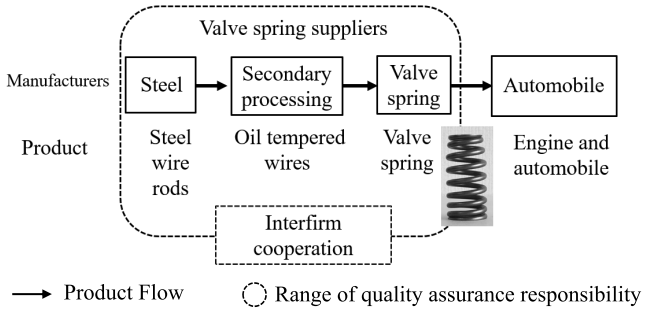

Fig. 4. Supply chain of valve springs and interfirm cooperation.[5,23] Valve spring suppliers include steel manufacturers, secondary processors, and valve spring manufacturers. The dotted line shows the cooperation of the three types of suppliers on quality assurance responsibilities.

ance of valve springs are based on automobile manufacturers' requirements and the supply chain pattern is quite different from that of steel nails in Fig. 1.

The quality assurance of steel nails is based on JIS and that of valve springs on the users' requirements. In this way, the difference in business practices for quality assurance is considered one of the factors which differentiates the supply chain patterns.

On the basis of the above discussions, it seems that supply chain patterns for the quality assurance of steel products are classified into the steel nail pattern and the valve spring pattern according to the business practices of each supply chain. When the business practice for quality assurance in the chain is based on standard specifications such as JIS, it appears that the supply chain tends to have the steel nail pattern. On the other hand, when based on the users' requirements, it appears that the supply chain tends to have the valve spring pattern.

In this section, the analyses focused on product transactions in the supply chain. According to the suggestion by Williamson[7] and Baldwin[8] that analysis of the production system, the supply chain in this study, requires technological and natural scientific perspective, the next section explores the influence of natural scientific understanding level about physical phenomena in steel on the behaviors of suppliers to discuss the difference between the two supply chain patterns in further detail.

4. Influence of Natural Scientific Understanding Level about Physical Phenomena in Steel

In this section, in order to achieve the research objective, the study seeks the natural scientific reasons which differentiate the two supply chain patterns. Thus, this study focuses on the microstructures of steel for the two products and analyzes the physical phenomena in steel, which may give the influence on supply chain patterns. The information of the microstructures of steel for the two products was collected by the document surveys mainly from ISIJ International, *Tetsu-to-Hagané*, and physical metallurgy journal.

The major production processes of steel nails are drawing and forging as described in section 3. According to the document surveys,[19] JIS information,[21] and the interviews with steel nail manufacturer, microstructures of steel nails are ferrite and/or pearlite from wire rods as raw materials to final products consistently. In other words, the construction of microstructure of steel nails is assumed to be simple enough for suppliers to adapt to changes in each manufacturing condition. It is considered that the microstructure and work hardening phenomena of steel nails are understood to some extent as natural scientific mechanism.

In the case of valve springs, the situation is different. Regarding the information of microstructures in steel of valve springs, it was obtained by the document surveys that quenching and tempering are performed in the secondary processing, and that tempered wires gain significant strength as a material for the valve spring at this stage.[23,26–28] In the quenching process, the microstructure of the carbon steel changes from ferrite and/or pearlite to a martensite structure through an austenite phase at high temperature in order to obtain a certain hardness of steel.[26] This change of the microstructures in steel from austenite to martensite is called martensitic transformation.[29–31] The hardening phenomenon of steel through this martensitic transformation is called martensite hardening in this study.

Studies on the process of high strength steel by combining the rolling process and the heat treatment began in the late 1950s in Europe and the United States. In the 1960s and the early 1970s, research on martensite was active worldwide.[32] Recent studies on martensite hardening are as follows: Ohlund *et al.*[33] for grain defining, Hidaka *et al.*[34] for carbon in solution, Man *et al.*[35] and Tsuchiyama *et al.*[36] for dislocation hardening, and Ping *et al.*[37] for carbide precipitation. In addition, other studies from various angles, such as crystallography,[38] thermodynamics,[39] elasto-dynamics and mathematical simulations[40] have made significant progress with understanding of martensitic transformation and hardening over the decades. However, these studies do not perfectly clarify the scientific mechanisms of martensite hardening. In a recent representative study on martensite grain structure, Iwashita *et al.*[41] demonstrate that the formation of martensite is not yet understood. This fact was reaffirmed by the interviews with martensite researchers' comments that the hardening mechanism of martensite has not yet been perfectly clarified. Thus, the natural scientific mechanism of martensitic transformation and hardening has not been sufficiently understood at the atomic and molecular level.

The interviews were conducted to learn about the cooperative behaviors of suppliers in the valve spring supply chain described in section 1, by asking the interviewees in what technical context the suppliers cooperate with one another. It was obtained by the interviews with valve spring manufacturer that if one of the suppliers in the supply chain was required to change its manufacturing conditions significantly, the change clearly spreads to all suppliers in the chain. In addition, according to the interview with wire rods manufacturer, when one supplier in the supply chain changes manufacturing conditions, it becomes very difficult for the company alone to maintain the same valve spring quality targets. It is considered from the interviews above that if one of the suppliers has to change its manufacturing conditions, the cooperation between all suppliers is necessary.

In order to achieve the research objective, this section seeks the scientific reasons behind the difference of supply chain patterns between steel nails and valve springs. The

fact clarified in this section that the scientific mechanism of martensite hardening which determines the quality of the valve spring has not been sufficiently understood complicates the process for constructing martensitic microstructure of steel. Further interviews with steel manufacturer and martensite researchers were carried out to get the comments as to the relationships between the natural scientific understanding level about physical phenomena in steel and the suppliers' behaviors in the supply chain. The comments are as follows:

- If the microstructure of the steel was determined, the characteristics of the steel would be determined by the knowledge based on accumulation of past experiences.
- Since the mechanism of the martensitic transformation and hardening is not understood sufficiently, the theoretical method for further quality improvement is not known.
- Therefore, suppliers have to find the optimum combination of manufacturing conditions throughout the manufacturing process by trial and error to achieve the new quality targets.
- This search process cannot be completed by one company in the supply chain, and cooperative relationships are inevitable.

In the earlier studies, Ludwig, *et al.*[42] describe that the resource exploitation must be determined by trial and error for the complexity of the underlying system, such as the case of the construction of martensite for the new product development in this study. Furthermore, Wagner[43] suggests that it is essential for suppliers to cooperate with one another to deal with complexity. These suggestions in the previous studies can be applied to this study that the valve spring suppliers cooperate with one another to find the optimum manufacturing conditions to achieve the quality targets through trial and error.

When any defects are found in the product after delivery, suppliers work together in a cooperative manner to investigate the causes of the failure and countermeasures, as is the case of new product development. This is because the manufacturing conditions of the valve spring are not based on a scientific mechanism and the cause of the failure cannot be predicted in advance. Thus, quality assurance cannot be completed until the actual use of the product. For this reason, it is considered that the business custom called performance guarantee,[5,6] in which the entire suppliers fulfill the responsibilities for quality assurance after the product delivery, has been established.

What have been found so far in the valve spring supply chain are as follows: as the scientific mechanism of martensitic transformation and hardening is not fully understood, the process for constructing the martensitic microstructure of steel becomes complex; for this reason, when the quality targets of products change such as the case of developing new products, it is necessary for all suppliers in the supply chain to find optimum manufacturing conditions to satisfy the new quality targets through trial and error in a cooperative manner. From the above investigations and discussions, it becomes clear that the range of quality assurance responsibility of the valve spring supply chain encompasses the entire suppliers, and the cooperation shown in Fig. 2 or Fig. 4 is inevitably constructed.

Table 2. Supply chain patterns of steel nails and valve springs, and conditions determining the pattern of a steel product.

Supply chain pattern	Steel nail pattern	Valve spring pattern
Business practice for quality assurance	Based on standard specifications such as JIS	Based on users' requirements
Understanding level about physical phenomena in steel	Relatively understandable	Insufficient

On the other hand, in the case of steel nails, it was obtained by the document surveys[18–20] and confirmed by the interviews with a steel nail supplier that the manufacturing processes of steel nails are simple because the major processes, drawing and forging, do not involve the martensitic transformation. As for steel nails, the physical structure of the steel is relatively understandable, thus, the quality assurance in the chain from upstream to downstream is based on JIS, and each supplier completes its own quality assurance responsibility for its own product. Consequently, there is no need for interfirm cooperation between suppliers, and the range of each company's business is the same as the range of quality assurance responsibility. For these reasons, the supply chain pattern of steel nails is close to conventional supply chain pattern in Fig. 1.

This section confirms that the difference in the level of natural scientific understanding of physical phenomena in steel can be the second factor which differentiates the supply chain patterns.

On the basis of the discussions in section 3 and 4, the business practice in the supply chain of each steel product and the level of natural scientific understanding of physical phenomena in steel are considered to be determinants of the supply chain pattern in the quality assurance of the product. In the case that the business practice is based on standard specifications such as JIS and the understanding of physical phenomena in steel is relatively advanced, the supply chain of the product tends to have the steel nail pattern as shown in Fig. 1. On the other hand, in the case that the business practice is based on the users' requirements and the understanding of physical phenomena in steel is insufficient, the supply chain of the product tends to have the valve spring pattern as shown in Fig. 2. The conditions determining the supply chain pattern of a steel product are summarized in **Table 2**. The results of this study suggest that if the understanding of the strengthening mechanism of steel by martensitic transformation is deepened, quality assurance for the product could change from users' requirements type to the JIS type, and the supply chain pattern of valve springs could change into the steel nail pattern.

Although the examples of this case study are of steel nails and of valve springs, business practice for quality assurance and the level of natural scientific understanding of physical phenomena in steel are factors that all steel products have. Therefore, it is considered that the knowledge obtained in this study is applicable to other steel products. However, specific analyses of the supply chains of other steel products should be the subject of future research.

5. Conclusions

This study investigated the supply chain patterns of steel products from the viewpoints of the range of quality assurance responsibility and understanding of physical phenomena in steel. Focusing on the difference between the supply chain pattern of steel nails for common use and that of valve springs for automobiles, the study revealed the causes of the differences and the influence of natural scientific understanding level about physical phenomena in steel on supply chain patterns as follows:

(1) One of the factors responsible for the difference in supply chain pattern between steel nails and valve springs is the difference in the business practices for quality assurance, namely JIS base for steel nails and users' requirement base for valve springs. While the quality assurance responsibilities of steel nails in the conventional supply chain pattern are based on JIS regulations, those of valve springs are not based on JIS but on requirements of automotive manufacturers, and valve spring suppliers keep seeking out optimum manufacturing conditions to respond to the higher quality requirements of automobile manufacturers than JIS.

(2) The second factor is the difference in the level of natural scientific understanding of physical phenomena in steel. In the manufacturing process of valve springs, because the scientific mechanism of martensite hardening has not been fully understood, the construction of martensitic microstructures in steel that determines product characteristics becomes complex, whereas the microstructures of steel nail is relatively understandable. As a result, unlike the case of steel nails, valve spring suppliers cooperate with one another to find the optimum manufacturing conditions to achieve the quality targets of the final product by trial and error, and the range of each supplier's quality assurance responsibility covers the entire supply chain.

(3) The conditions that determine the supply chain pattern of a steel product for quality assurance are clarified as follows:

- business practices for quality assurance in each product
- the level of natural scientific understanding of physical phenomena in steel

Although this study focuses on steel nails and valve springs, this finding is applicable to other steel products since all steel products have above two factors.

Acknowledgments

The authors would like to extend their gratitude to Professor Shigekazu Morito at Shimane University and Associate Professor Yuhki Tsukada at Nagoya University for their insightful comments and suggestions. The authors would also like to thank all of those who responded to our interviews.

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