Development of Manufacturing Process "HISTORY" for Producing Innovative High Frequency Welded Steel Tubes with Excellent Properties^{*}





Takaaki Toyooka Ph. D. General Manager, Tubular Products & Casting Lab., Technical Res. Labs.

Motoaki Itadani Manager, Quality Assurance Sec., Products Service & Development Dept., Chita Works



Akira Yorifuji Senior Researcher, Tubular Products & Casting Lab., Technical Res. Labs.

1 Introduction

With the intensification of environmental problems, improved fuel mileage in automobiles has increasingly been required. Automobile weight reduction and improvements in the engine have been carried out to increase fuel mileage, one of the effective means of realizing weight reduction is the adoption of hollow parts using electric resistance welded (ERW) steel tubes.

ERW steel tubes are comparatively economical and possess high dimensional accuracy, and can also be produced with thinner wall thicknesses. Owing to these advantages, use of ERW steel tubes had risen steadily in recent years.¹⁾ However, as the properties required for steel tubes used in automobile parts have become stricter, development of a new steel tube which possesses both high strength and excellent formability has been desired. However, it was difficult to realize both high strength and excellent formability in conventional ERW steel tubes which were manufactured by cold rollforming of steel band. This was because the work-hardening caused by the cold roll-forming makes the ductility of steel tube inferior to that of the material steel band.²⁾ At the same time, quench-hardening caused by

Synopsis:

Aiming at weight reduction, the improvement of collision safety and manufacturing cost reduction in the automobile industry, the amount of steel tubes used for automotive parts has been increasing in recent years. The increase of strength and formability of ERW steel tubes is essential for further weight reduction and wider application. However it was difficult to realize high strength and formability at the same time in a conventional ERW steel tube. The formability of ERW steel tubes is not sufficient because the sheet material is subjected to work-hardening in the cold roll forming and the welded portion is subjected to weld-hardening during the electric resistance welding. In order to overcome these technological difficulties, Kawasaki Steel has developed a new steel tube manufacturing method termed the HISTORY (high speed tube welding and optimum reducing technology), which consists of a newly developed thermo-mechanical control process based on new metallurgy by means of the world's first warm stretch reducing. The HISTORY tube with high strength and excellent formability has been successfully manufactured in a production line which was built in October 2000 at Chita Works.

rapid cooling after welding does the same in the welded portion.

To overcome these problems, Kawasaki Steel has developed the HISTORY process as a next-generation manufacturing technology for ERW steel tubes, and succeeded for the first time in the world in producing a high performance electric resistance welded steel tube, called the HISTORY steel tube, possessing both high strength and excellent formability, which had been difficult to realize simultaneously in conventional ERW steel tubes. As part of this new process, Kawasaki Steel developed the world's first on-line moderately high temperature thermo-mechanical treatment and applied this technology in a practical operation, realizing on-line control of the mechanical properties of steel tubes for the first time in the field of steel tube manufacturing. The HISTORY

^{*} Originally published in Kawasaki Steel Giho, 33(2001)4, 145– 150

process was adopted in a new line which was constructed at Kawasaki Steel's Chita Works, and commercial production began in October 2000.

This report describes the concept for the development of the high performance HISTORY steel tube, the metallurgy which makes it possible to realize excellent properties, in the HISTORY steel tube and the properties of the HISTORY steel tube for practical use.

2 Concept for Development of the HISTORY Steel Tube

In the automotive industry, the use of ERW steel tubes has increased in recent years from the viewpoints of automobile weight reduction, improved collision safety, and cost reduction. These ERW steel tubes are required to satisfy the specifications of automobile parts with respect to thin walled materials, excellent dimensional accuracy, and cost effectiveness. Recently, required specifications extend to higher strength and improved formability.

The biggest problem in the manufacture of small diameter ERW steel tubes for machine structural use. which includes steel tubes for automobile part, is removal of the inner and outer weld beads at the high frequency induced welded portion, as shown in Fig. 1. In particular, in removal of the inner weld bead, it is necessary for checking the bead scarfed surface level to hold the steel tube manufacturing mill and remove a part of the welded steel tube by gas cutting. The height of the inner scarfing bite is then adjusted to make the difference between the bead scarfed surface level and the tube surface level within the value specified in the product standard. When strict accuracy is required, this adjustment process must be repeated a number of times. For many years, this has been the biggest problem in the manufacture of ERW steel tubes, and it has also had a significant effect on tube quality.

The starting point for the development of the HIS-TORY steel tube was the idea of eliminating the need for bead scarfing with ERW steel tubes. Because the two



Fig. 1 Schematic illustration of bead cutting in electric resistance welding steel tube manufacturing process

edges of the steel band are melted, bead scarfing is necessary in order to remove the molten metal (slag) adhering to the outer and inner surfaces of the tube. However, it was considered that, if this slag formation could be eliminated, the increased wall thickness portion which occurs due to upsetting could be flattened by rolling, resulting in scarfing unnecessary. This was followed by the idea that diffusion welding would be possible if the entire mother tube was first heated to the moderately high temperature range before welding, and the edges of the steel band were then heated to a temperature just below the melting point and joined by upsetting. This diffusion welding process was considered to be a method of joining the edges of the steel band by high frequency electric resistance welding instead of melting.

Moreover, the idea of heating the mother tube to the moderately high temperature range was conceived as part of a process which would include warm-reducing of the tube after welding. In 1994, when this warm-reducing process was conceived, the forming process using the moderately high temperature range (around 700°C) was still at a stage where it was virtually unknown in practical examples,³⁾ and was found only in some research reports.^{4,5)} The development of ultra fine grain steel using high reduction rolling in moderately high temperature range had not yet begun (started in 1997) in the STX 21 Project (National Research Institute for Metals, part of the former Science and Technology Agency)⁶⁾ or the Super Metal Project (Metal Material Research and Development Center, part of the former Ministry of International Trade and Industry),⁷⁾ which are now being promoted as national projects and are attracting intense international interest.

At the present stage, the original idea of electric resistance diffusion welding in the upstream process of welding the edges of the steel band is not applied to the high performance HISTORY steel tube. Conventional electric resistance welding is adopted, as shown in **Fig. 2**. However, in the downstream process of reducing the steel tube, high-reduction reducing in the moderately high temperature range was developed, and the creation of steel tubes with excellent properties based on new metallurgy has been realized for the first time in the world.

Up to this time, the importance and value of warmreducing had scarcely been appreciated. However, in the present development, the authors boldly challenged this unexplored region, leading to important new metallurgical applications.



Fig. 2 Manufacturing process of the HISTORY tube

KAWASAKI STEEL TECHNICAL REPORT

3 New Metallurgy of the HISTORY Steel Tube and Its Mechanism

The manufacturing process of the HISTORY steel tube is shown in Fig. 2. Using the CBR (chance-free bulge roll) forming mill developed by Kawasaki Steel,^{8,9)} the steel band is roll-formed into a tube shape in the low temperature range (room temperature), and the edges are welded by electric resistance welding. As one advantage of the CBR mill, it is possible to stabilize the forming and welding of thin-walled tubes. The tube is heated after this process, and is then reduced by a stretch-reducer. With conventional tubes, reducing is performed in the relatively high temperature range (900 ~ 1100° C), where deformation resistance is small, as in the case of hot rolled steel sheets. However, with the HISTORY steel tube manufacturing process, as shown in Fig. 3, it is possible to manufacture tubes with the various properties described below with high productivity by rolling in the moderately high temperature range (650 ~900°C), where the rolling load is several times higher than that in the hot region.

Rolling in this warm region, and especially rolling in the dual phase temperature region, is difficult with steel sheets, and is a technology which was realized in a practical application for the first time with the HISTORY steel tube. With steel sheets, shape defects easily occur if rolling is performed at around the transformation temperature, as in the dual phase temperature region, because the material temperature drops in the transverse direction at the sheet edges. Furthermore, as will be discussed later, rolling below the dual phase temperature is not possible with steel sheets, because the mechanical properties of the steel sheet, such as the r-value, etc., will deteriorate if rolling is performed in the warm region. Figure 4 is a schematic illustration of the effect of warm-reducing on the strength and formability of steel tubes. With the HISTORY steel tube, the grain size is refined by reducing in the warm region, thereby obtaining high strength. At the same time, excellent formability can also be obtained due to fine dispersion of the secondary phase and precipitates, formation of a



Fig. 3 Comparison of rolling temperature between the developed process and conventional process



Fig. 4 Concept of warm reducing for high strength and excellent formability



Fig. 5 Mechanical properties of the HISTORY steel tube and ERW steel tube

dual phase structure, and formation of the rolling texture having high *r*-value.

As shown in **Fig. 5**.¹⁰ warm-reducing is an innovative manufacturing method which makes it possible to produce a wide range of specialized products, from high strength materials to materials with excellent formability, which could not be obtained with conventional ERW steel tubes or with steel sheets, using a steel with the same chemical composition. This range of properties is achieved by control of the reducing condition due to obtaining appropriate microstructure and texture. For example, in the case of the low carbon steel shown in Fig. 5, control of the reducing temperature makes it possible to manufacture tubes with approximately 20% higher elongation at the same strength level, or with approximately 20% higher strength at the same elongation, in comparison with conventional ERW steel tubes. Furthermore, the strength and elongation of the HIS-TORY steel tube show a better elongation-strength balance than that of high grade ERW steel tubes using dual phase steel. These effects are discussed in the following.

4 Features of the HISTORY Steel Tube

4.1 Solution to Quench-Hardening at Electric Resistance Welded Portion

Figure 6 shows the hardness distribution around the



Fig. 6 Hardness distribution of welded portion

welded portion in the HISTORY steel tube and an ordinary ERW steel tube.^{10,11)} The welded portion of the ERW steel tube is hard and poor in formability due to the quenched structure which is formed by electric resistance welding. With conventional ERW steel tubes, it had been necessary to perform offline normalizing in order to eliminate the quench-hardening at the welded portion. In contrast, the welded portion of the HISTORY steel tube has the same level of hardness as the base metal because the quenched structure decomposes into ferrite and fine carbides, which is the same structure as in the base metal. As a result, the HISTORY steel tube shows improved formability.

4.2 Grain Refinement

The microstructures of the HISTORY steel tube and ERW steel tube are shown in **Photo 1**. In the HISTORY steel tube, high strength is obtained by refining the grain size (including subgrains) to approximately $1 \sim 2 \mu m$ by high-reduction reducing in the warm region. This effect is a new mechanism called continuous recrystallization of ferrite, and was developed by Kawasaki Steel in advance of the researches which are currently being carried out in the STX21 and Super Metal Projects.^{12,13)} Because high strength is obtained by grain refining, there is little need to use special elements such as Cu, Cr, Mo, V, Ti, etc. in the HISTORY steel tube. Consequently, the HISTORY steel tube is also considered to be superior in recyclability.

However, it is difficult to apply a simple fine-grained



Photo 1 Microstructure of the HISTORY steel tube and ERW steel tube



Photo 2 SEM of the HISTORY steel tube and ERW steel tube

steel as a material for automobile part use, in which formability is required. This is due to the problem that grain refinement secures high strength, but also causes a remarkable decrease in formability. With warm-reducing, it is possible to obtain both high strength and excellent formability because, in addition to high strength due to grain refinement, formability is improved by fine dispersion of the secondary phase and high *r*-value owing to the unique texture formed by reducing, as discussed in the following. By using this new metallurgy, the HIS-TORY steel tube realizes the mutually incompatible properties of high strength and excellent formability, which had not been achieved with conventional technologies, for the first time in the world.

4.3 Finely Dispersed Secondary Phase (On-line Spheroidizing of Cementite)

Photo 2 shows the microstructures of a 0.42%C high carbon HISTORY steel tube and a conventional ERW steel tube.¹⁴⁾ In the HISTORY steel tube, cementite is spheroidized and finely dispersed in the as-warm reduced condition. Because the cementite lamella in pearlite can be broken up and dispersed mechanically by warm-reducing, it is possible to complete spheroidizing in several seconds without spheroidizing annealing process, which requires several tens of hours with hot rolled steel sheets. This means that formability can be improved in comparison with hot rolled steel sheets.

4.4 High r-Value

The texture of the HISTORY steel tube is shown in **Fig. 7**. During rolling in the warm region, the rolling texture is formed in a way which facilitates the deformation of rolling. As a result, as shown in **Fig. 8**, it is possible to obtain a rolling texture which facilitates the deformation of the circumferential reduction direction compared with that of the normal direction in the reducing process. In other words, the obtained texture has a high *r*-value (= strain in transverse direction/strain in normal direction in tensile test) in the rolling direction. Conversely, in ordinary sheet rolling, a rolling texture with a low *r*-value is formed because the reduction direction. This is one reason why sheet rolling in the warm region can-

KAWASAKI STEEL TECHNICAL REPORT



Fig. 7 Texture of the HISTORY steel tube, EBSD



Fig. 8 Comparison of deformation between in reducing and rolling



Fig. 9 Lankford value of the HISTORY steel tube

not be performed. In comparison with the recrystallization texture which is utilized for high *r*-value in steel sheet, formation of the rolling texture is not easily affected by solute carbon, nitrogen, precipitates, or the secondary phase. Thus, because the HISTORY steel tube employs a rolling texture, it is possible to obtain high *r*values with a number of types of steel, such as low carbon steels other than extra-low carbon IF steel, high carbon steels, dual phase steels, stainless steels, and other steels in which obtaining a high *r*-value is difficult with steel sheets that utilize the recrystallization texture for high *r*-values. As shown in **Fig. 9**, extremely high *r*values, approximately 2 to 4 times higher than those of hot rolled steel sheets, can be obtained through the HIS-TORY process.

4.5 Dual Phase Structure

By appropriately controlling the reducing tempera-



Fig. 10 Effect of reducing temperature on mechanical properties

 Table 1
 Mechanical properties of the HISTORY steel tube

-	YS (MPa)	TS (MPa)	uEl (%)	El (%)
_	618	1 043	14.3	23.1
				IIS12A. 2.6 mmt

ture, a dual phase structure of ferrite plus martensite, bainite, or residual austenite, etc. can be obtained with relative ease in the HISTORY steel tube. Figure 10 shows the effect of the reducing temperature on tensile properties. Reducing in the dual phase region of ferrite and austenite results in a dual phase structure consisting of ferrite and martensite, and thus makes it possible to produce steel tubes with a low yield ratio (yield strength/tensile strength) and excellent formability. It is also possible to obtain a low yield ratio and excellent formability in ultra high strength steel tubes with a tensile strength as high as 1 000 MPa or more, as shown in Table 1, offering that the HISTORY process is an effective method of improving the formability of high strength materials.

5 Basic Forming Properties of the HISTORY Steel Tube and Examples of Application

5.1 Basic Forming Properties

5.1.1 3-point bending formability (JIS 11; 15 mm $\phi \times 1.8$ mmt)

A 3-point bending test of specimens with the mechanical properties shown in **Table 2** was performed, **Photo 3** shows a comparison of the bending performance of the HISTORY steel tube and a conventional ERW steel tube.¹¹⁾ Buckling occurred in the ERW steel tube before 180° bending was completed, but in contrast, it was possible to bend the HISTORY steel tube to 180° without buckling.

Table 2Mechanical properties of tested tubes, JIS11

	YS (MPa)	TS (MPa)	El (%)
HISTORY	530	575	32
ERW	480	509	18



Photo 3 Appearance of bent tubes

5.1.2 Stretch bending formability

A stretch bending test of specimens with the mechanical properties shown in **Table 3** was performed under the test conditions shown in **Fig. 11**. Bending was performed while applying axial pressure with a pressure die. Figure 11 shows a comparison of the reduction in the wall thickness of the HISTORY steel tube and the ERW steel tube. In spite of the fact that the tensile strength of the HISTORY steel tube was higher than that of the ERW steel tube, the reduction ratio of wall thickness in the HISTORY steel tube was approximately 10% smaller than that in the ERW steel tube. This is attributable to the high *r*-value of the HISTORY steel tube.

5.1.3 Fatigue strength

A bending fatigue test using a cantilever beam pulsated with negative and positive values was performed with the specimens used in the above-mentioned 3-point bending test. **Figure 12** shows the *S-N* diagram of this fatigue test. The increased strength of the HISTORY steel tube improved the fatigue limit by approximately 20% in comparison with that of the ERW steel tube.

Table 3 Mechanical properties of tested tubes, JIS11



Fig. 11 Variation of wall thickness of the HISTORY steel tube and ERW steel tube



Fig. 12 S-N diagram by bending fatigue test

5.2 Examples of Application to Automobile Parts

The HISTORY steel tube is increasingly used in automobile parts, as shown in **Fig. 13**, for advantage of the outstanding properties of this new product. Here, several examples of actual application will be presented.

The shapes of automobile structural parts such as the stabilizer, twist beam, and lower arm, as shown in Fig. 14 have tended to become even more complex as automobile bodies have become more compact. This has promoted the need for excellent formability to steel tubes, and in particular, for small radius bending formability. On the other hand, it is necessary to use non-heat treated high strength materials, which are generally poor in formability, in order to reduce parts weight and reduce material cost. Because the HISTORY steel tube provides both high strength and excellent formability in the as rolled condition, it is a suitable tube for these requirements. Figure 15 is a schematic illustration of the manufacturing process for lower arms made of steel tubes. By using the HISTORY steel tube, which has satisfactory bending formability, it is possible to manufacture lower arms from steel tubes. Because lower arms



Fig. 13 Steel tubes applied to automobile parts



Fig. 14 Automotive parts examples

KAWASAKI STEEL TECHNICAL REPORT



Fig. 15 Forming process of lower arm

made of steel tubes have a closed section structure, rigidity can be secured even with thin walled parts, enabling a weight reduction of approximately 30%, in comparison with lower arms made of steel sheets.

To reduce weight in the drive shaft and other drive train parts, hollow parts made of steel tubes have been progressively adopted. Since extremely high fatigue strength is necessary, these drive train parts are manufactured by quenching and tempering high carbon ERW steel tubes. The high carbon ERW steel tubes used in this type of application is subjected to large work-hardening as a result of cold roll-forming, as well as quenchhardening at the seam position. Consequently, heat treatment is necessary before forming. However, because the microstructure of high carbon steel contains a large amount of pearlite, adequate formability cannot necessarily be obtained, even if normalizing is performed. Although long-time spheroidizing annealing for several tens of hours before forming is conceivable as a means of improving formability, manufacturing energy consumption becomes excessive and the cost is extremely high.

With the HISTORY steel tube, as shown in Photo 2, it is possible to spheroidize cementite on-line by the warm-reducing process. This means that high carbon steel tubes with excellent formability can be manufactured with high productivity by appropriate selection of the reducing temperature. Use of this high carbon HIS-TORY steel tube made it possible to manufacture a monoblock hollow drive shaft, as shown in **Fig. 16**, achieving weight reduction of approximately 20% in



Fig. 16 One-piece type and three-piece type drive shafts

comparison with the conventional three-piece drive shaft. Furthermore, because the formability of the HIS-TORY steel tube is more excellent compared with that of the same carbon content ERW steel tube, it is also possible to substitute higher carbon content HISTORY steel tube for conventional ERW steel tube, resulting in obtaining higer strength.

5.3 Use as Eco-Material

Special elements such as Cu, Cr, Mo, Ti, Nb, V, etc. are generally added in order to use transformation hardening or precipitation hardening to strengthen steel materials, but there are cases in which these elements cause problems in recycling. With the HISTORY steel tube, addition of special elements can be held to the minimum because high strength is obtained by grain refining. In general, grain refining secures high strength but reduces formability. However, with the HISTORY steel tube, both high strength and excellent formability can be secured simultaneously because, in addition high strength due to grain refinement, formability is improved by finely dispersion of the secondary phase and high *r*-value owing to the unique texture formed by reducing. This high r-value due to the warm-reducing eliminates the need to use an extra-low carbon IF steel, as in sheet rolling, thereby reducing refining energy consumption for decarburization. At the same time, because there is little need to use special elements such as Ti, Nb, V, etc. those are added to extra-low carbon IF steel, leading to the excellent recyclability of the HISTORY steel tube. Moreover, with the HISTORY steel tube, it is possible to omit the long time heat treatment such as cementite spheroidizing, making advantageous for energy consumption.

As described in the foregoing, use of the HISTORY steel tube as a global-environment friendly eco-material can be expected.

6 Conclusion

The HISTORY process was developed as a new manufacturing process for electric resistance welded steel tubes, making it possible to manufacture the high performance HISTORY steel tube, which satisfies the mutually incompatible requirements of high strength and excellent formability. High performance is achieved in the HISTORY steel tube by using a new in-line thermomechanical treatment technology called warm-reducing to create excellent new material properties. Large expectations are placed on future applications.

The results obtained in this development are summarized below.

(1) It was possible to develop a new metallurgy, including high *r*-values, etc., by forming ultra-fine grains and a high *r*-value owing to a favorable rolling texture etc., which were achieved by warm-reducing for the first time in the world.

- (2) High strength is obtained in the HISTORY steel tube by refining grains (including subgrains) to approximately $1 \sim 2 \mu m$ by high-reduction reducing in the warm region. This effect is attributable to a new mechanism which is called continuous recrystallization of ferrite.
- (3) In addition to grain refinement, fine dispersion of a secondary phase is possible in the HISTORY steel tube. On-line spheroidizing of cementite can also be achieved, making it possible to omit off-line spheroidizing annealing.
- (4) With the HISTORY steel tube, a rolling texture is formed by high-reduction reducing in the warm region, making it possible to secure high *r*-values in the tube rolling (longitudinal) direction. High *r*-values by warm-reducing also can be obtained in many types of steels other than extra-low carbon IF steel, such as low carbon steels, high carbon steels, dual phase steels, stainless steels, and other steels in which obtaining a high *r*-value is difficult with steel sheets that utilize the recrystallization texture for high *r*value. The HISTORY steel tube shows extremely high *r*-values, approximately 2 ~ 4 times higher than those of hot rolled steel sheets.
- (5) The mutually incompatible properties of high strength and excellent formability can be secured in the HISTORY steel tube because, in addition to high strength due to grain refinement, enhanced formability is obtained by fine dispersion of the secondary phase and formation of a unique rolling texture by reducing having high *r*-value.
- (6) By appropriately controlling the reducing temperature, a dual phase structure comprising ferrite plus martensite, bainite, or residual austenite, etc. can be created with comparative ease in the HISTORY steel tube. Thus, it is possible to realize high strength combined with excellent formability.
- (7) By applying warm-reducing, which is a new thermo-mechanical treatment technology, it is possible to create materials for automobile parts which possess excellent properties not found in conventional ERW steel tubes, contributing to weight reductions of

 $20 \sim 30\%$ in automobile parts.

(8) Because the HISTORY steel tube realizes high strength and excellent formability without addition of special elements, the scrap material has satisfactory recyclability. Consequently, use as an eco-material is also expected.

In conclusion, the authors wish to express that portions of this development were carried out using a grant for the development of practical technologies for rational energy use from the former Ministry of International Trade and Industry (MITI). We also wish to express our deep appreciation to all those at affiliated companies who cooperated in this development work.

References

- S. Inoue: "Development of Mechanical Tubes for Automobiles", The 171st and 172nd Nishiyama Kinen Gijutsu Kouza, (1999), 44
- T. Toyooka, Y. Hashimoto, and M. Gunji: Kawasaki Steel Giho, 32(2000)1, 53
- Y. Nomiyama, T. Ishikawa, T. Hasegawa, and T. Haji: CAMP-ISIJ, 7(1994), 1834
- H. Sekiguchi, K. Kobatake, K. Osakada, and K. Kubo: J. of the Jpn. Soc. for Tech. of plasticity, 24(1983)271, 873
- 5) F. Togashi, T. Imae, A. Ejima, and Y. Sayama: Tetsu-to-Hagané, 67(1981)4, 307
- T. Hayashi, O. Umezawa, S. Torizuka, T. Mitsui, K. Tsuzaki, and H. Nagai: CAMP-ISIJ, 11(1998), 1031
- M. Niikura, T. Yokota, K. Sato, T. Shiragami, M. Fujioka, T. Tomita, Y. Adachi, S. Nanba, T. Matsukura, and I. Hagiwara: *CAMP-ISIJ*, **11**(1998), 1021
- T. Toyooka, Y. Hashimoto, Y. Kusakabe, and J. H. Lobello: Proc. 10th World Tube Cong., Chicago (USA), Oct. (1994)
- T. Toyooka, Y. Hashimoto, K. Kobayashi, S. Itatani, T. Ide, and Y. Nishida: *Kawasaki Steel Giho*, 22(1990)4, 18
- T. Toyooka, A. Yorifuji, M. Itadani, M. Nishimori, and Y. Kawabata: *CAMP-ISIJ*, **12**(1999)2, 302
- T. Toyooka, A. Yorifuji, M. Itadani, Y. Hashimoto, M. Nishimori, Y. Kawabata, M. Kodaka, and Y. Koyama: Proc. of 1999 Spring JSTP, (1999), 189
- 12) Ex. The Nikkan Kogyou Shimbun, The Nikkei Sangyou Shimbun, The Nikkan Tekko Shinmbun of August 6, 1998
- 13) New Steel, Mar., (1999), 66
- 14) T. Toyooka, M. Itadani, A. Yorifuji, T. Okabe, M. Nishimori, Y. Kawabata, M. Kodaka, and Y. Koyama: Proc. of 2000 JSAE Annual Cong., No. 11–00, (2000), 9