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Ultra High-Strength Steel Sheets for Bodies, Reinforcement Parts, and Seat Frame Parts of Automobile —Ultra High-Strength Steel Sheets Leading to Great Improvement in Crashworthiness—[†]

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Abstract:

JFE Steel has developed and commercialized from TS780 to TS1 470 MPa grade cold-rolled ultra high-strength steel sheets with excellent press-formability, spot-weldability, and stability of mechanical properties and dramatically improve crashworthiness and fuel economy when applied in automobile bodies/reinforcement parts and seat frame parts. In response to strict formability requirements, the company conducted basic and detailed studies of changes in the microstructure and propagation of microscopic cracks during forming, and realized remarkable improvements in elongation and stretch-flange formability in comparison with conventional steels by adopting a low carbon equivalent design. In particular, as expanded application of TS980 MPa grade steel sheets is expected in the future, JFE Steel has developed a lineup of three types of TS980 MPa grade steels with different balances of mechanical properties corresponding to the material application and joining method. These products have already earned an excellent reputation with users. This paper introduces two newly developed TS980 MPa grade cold rolled steel sheets, one with excellent stretch-flange formability and the other for mechanical joining. Surface cracking in mechanical joining, which is strongly related to local elongation, has been suppressed by achieving a single martensite phase.

1. Introduction

In recent years, stricter requirements have been placed on the automobile body in order to achieve improved passenger safety, while there have also been heightened requirements for auto body weight reduction for improved fuel economy with the aim of reducing CO_2 emissions as a cause of global warming. In response to these requirements, automakers are increasingly applying high tensile strength steel to automobile bodies as a weight reduction measure. When used to improve the strength of auto body parts, high-strength steels make it possible to reduce weight by reducing part thickness.

Up to 1990, application of TS440–590 MPa grade high tensile strength steel to automobile structural parts was studied as substitute for conventional mild steel sheets from the viewpoints of improved collision safety performance (crashworthiness) and weight reduction, as described above. These sheets were improved to overcome poor press-formability and problems related to weldability and corrosion resistance, and played an important role in front collision parts, such as the front side member and others which absorb impact energy by

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deforming during collisions.

At the beginning of the 1990s, ultra high-strength steels of the TS780 MPa grade and higher were studied. These steels had conventionally been applied in bumper reinforcement materials and door impact beams and other safety reinforcement parts which were separated from the cabin, but in response to stricter safety and weight reduction requirements, their range of application has expanded to include the pillar and its reinforcement parts. This tendency was also clearly indicated in the ULSAB (Ultra Light Steel Auto Body) Project, which was carried out jointly by 32 steel makers in 15 nations beginning in 1994, and can be interpreted as the future direction for automobile structural parts.[1)]

In passenger automobile seats, seat structures which protect the passenger by using the seat itself to support the impact during collisions have been adopted to improve passenger safety, requiring both weight reduction and strength in the seat itself. TS980 MPa grade cold rolled steel sheets are increasingly used in seat frame parts to satisfy this need.

In response, JFE Steel carried out product development for a line of automotive steel sheets which lead the world in meeting the diverse requirements of automotive markets.[2,3)] As part of these efforts, JFE Steel commercialized high-formability ultra high-strength steel sheets which satisfy the above-mentioned requirements by making maximum use of the continuous annealing line (CAL) with a water quench (WQ) function shown in **Photo 1**, which makes it possible to obtain a wide range of strengths (TS780 to 1 470 MPa) and stable high mechanical properties with low alloy compositions.[4)]

This paper introduces JFE Steel's TS780−1 470 MPa grade cold rolled steel sheets, which have made it possible to achieve dramatic improvements in crashworthiness and weight reduction in automobile bodies. The basic material design concept and material properties of these products are described in outline, with particular emphasis on TS980 MPa grade sheets, in view of the expanding application of these materials to automobile body reinforcement parts and seat frame parts in recent years.

2. Development Concept of Ultra High-Strength Cold Rolled Steel Sheets

JFE Steel succeeded in commercializing ultra high-strength cold rolled steel sheets from the TS780 MPa grade to 1 470 MPa grade using the WQ-CAL, which was developed independently by JFE Steel and has the world's fastest cooling rate (exceeding 1 000ºC/s). Steel sheets manufactured with the WQ-CAL have the following features.

(1) Product line of high-formability steel sheets in grades TS780 MPa to 1 470 MPa capable of meeting a wide range of strength and forming requirements.
(2) Excellent spot weldability and delayed fracture resistance properties realized by low carbon equivalent composition design.
(3) Excellent stability of mechanical properties realized by uniform cooling and feedforward control in WQ.

Figure 1 shows typical heat cycles of the WQ-CAL. The microstructure (full martensite, DP (dual phase) microstructures) of the steel can be controlled by the temperature conditions in annealing. With DP steels, it is also possible to control the volume fraction of the hard secondary phase and hardness over a wide range by optimizing the water quenching temperature and tempering temperature. Ideal microstructure control was achieved

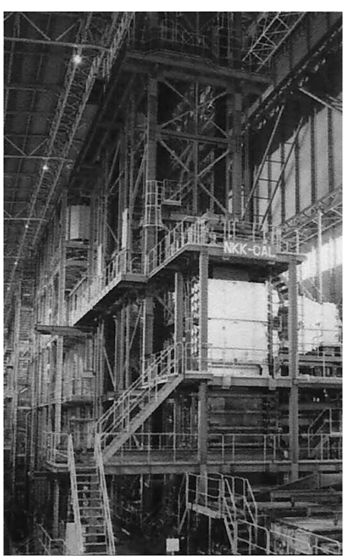

Photo 1 West Japan Works No. 3 continuous annealing line (WQ-CAL)

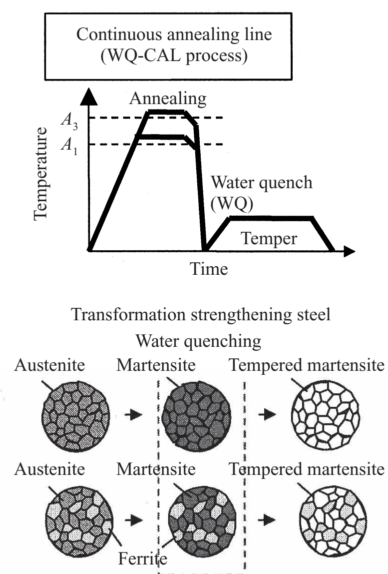

Fig. 1 Typical heat cycles of WQ-CAL, and schematic microstructures

Table 1 Line up of TS780–1 470 MPa grade cold rolled high strength steel sheets

TS grade	JFE Steel Standard	JFS Standard*1	Type	Thickness (mm)	Mechanical properties*2				C_{eq}*4 (mass%)
					YP(MPa)	TS(MPa)	El(%)	λ(%)*3	
780	JFE-CA780Y2	JSC780Y	Low YR	1.4	430	810	22	30	0.15
	JFE-CA780SF		High λ	1.2	600	830	19	80	0.12
980	JFE-CA980Y2	JSC980Y	Low YR	1.2	610	1 010	18	30	0.18
	JFE-CA980SF		High λ	1.2	740	1 020	15	60	0.18
	JFE-CA980SF2	–	Super λ	1.2	900	1 020	7	100	0.09
1 180	JFE-CA1180Y2	JSC1180Y	Low YR	1.2	950	1 210	14	30	0.23
	JFE-CA1180SF	–	High λ	1.6	1 030	1 230	7	60	0.17
1 370	JFE-CA1370	–	–	1.6	1 130	1 450	7	60	0.23
1 470	JFE-CA1470	–	–	1.6	1 200	1 510	7	60	0.23

*1 The Japan Iron and Steel Federation Standard
*2 Tensile specimen: Transverse direction, JIS No. 5
*3 λ: Hole expanding ratio according to JFS T 1001
*4 Carbon equivalent for spot welding: $C_{eq} = 1.5C + P + 3S$

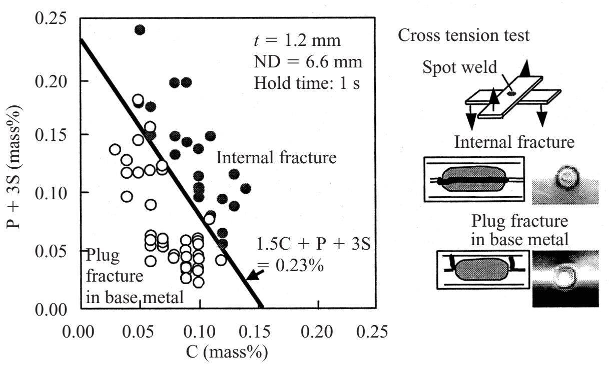

Fig. 2 Effects of C, P, and S contents on fracture type of spot-welded joint in cross tension test

by utilizing equipment functions that can realize these heat cycles, and a technology for producing different mechanical properties which correspond to a wide range of strength requirements and applications was established (**Table 1**).

As one important feature of the WQ-CAL, use of this technology makes it possible to secure strength and formability and low carbon equivalent composition design by minimizing additional elements, beginning with C, the soundness of welds, which is a concern with ultra high-strength steel sheets, can also be maintained. **Figure 2** shows the effect of additional elements on the cross tension properties of spot welded joints. Increases in the contents of C, P, and S encourage nugget fracture in the cross tension test of welded joints, and thereby reduce joint strength. Because a microstructure in which internal fracture occurs in the nugget is maintained, even in ultra high-strength steel sheets exceeding TS780 MPa, material design was performed with the carbon equivalent (C_{eq}) strictly controlled within the limit range shown by the line in Fig. 2 ($C_{eq} \leqq 0.23$), and delayed fracture in corrosion environments, which is a concern with ultra high-strength steel sheets of TS1200 MPa and higher, was overcome by using a low C_{eq} composition design and controlling the carbide morphology of the tempered martensite microstructure.[5)]

To improve dimensional nonconformance in parts due to springback, which is a problem when press-forming high tensile strength steel, strength deviations within coils have been reduced by rapid and uniform cooling control, which is an advantage of the WQ-CAL, resulting in stable strength and mechanical properties in the coil length and width directions. To improve coil-to-coil strength deviations, the steel composition is controlled within a narrow range in the steelmaking stage, and factors which cause strength fluctuations in the integrated manufacturing process from hot rolling to continuous annealing are controlled. As a result, strength deviations in TS780–1 470 MPa grade ultra high-strength steel sheets have been reduced to the same level as in TS590 MPa grade cold rolled sheets.

3. Recent Developments in TS980 MPa Grade Cold Rolled Ultra High-Strength Steel Sheets

3.1 TS980 MPa Grade Cold Rolled Steel Sheets for Automobile Body Structural (Reinforcement) Parts and Seat Frame Parts

JFE Steel improved the properties of TS980 MPa grade cold rolled steel sheets to meet a wide range of recent automobile part requirements and reconstructed this product line accordingly. Three types of TS980 MPa grade steel with the different features shown in **Table 2** were commercialized to meet the unique property requirements of various parts. These new steels are the low YR (yield ratio) type, high λ (hole expanding ratio) type, and super λ-type. The low YR type is a high ductility DP steel sheet for stretch-formed parts such as pillar parts, and features a low YP (yield point) and high ductility. The high-λ type also has a DP microstruc-

Table 2 Features of mechanical properties of 3 types of TS980 MPa grade cold rolled ultra-high strength steel sheets and their application to automotive parts

Type	Mechanical properties			Applicable parts
	YP	El	λ	
Low YR	Low	High	Low	· Structural parts of body in white ex. Center pillar (Reinforcement)
High λ	Medium	Medium	Medium	· Bumper reinforcement · Seat frame, Seat rail
Extra high λ	High	Low	High	· Seat parts (Mechanical clinch)

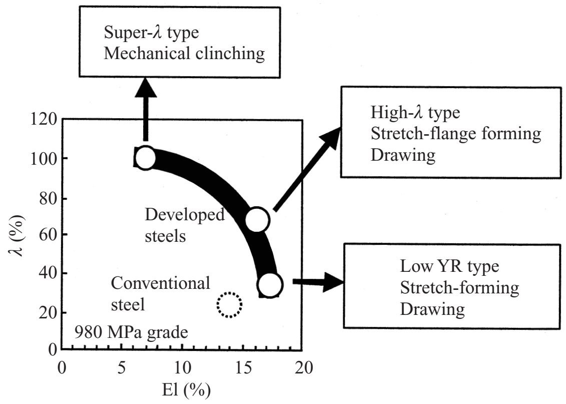

Fig. 3 Typical El-λ balance for newly developed TS980 MPa grade ultra-high strength steels

ture, but it has an excellent El-λ balance, which is evaluated based on the combination of elongation and stretch-flange formability. This product is widely applied to stretch-formed parts and seat parts. Super λ-type steel sheets achieve a hole expanding ratio surpassing that of TS440 MPa grade cold rolled steel sheets, and are also applied to mechanical joints which had conventionally been limited to low-strength materials such as mild steel and aluminum. Thus, this material makes it possible to reduce the weight of auto seat frames while also reducing part manufacturing costs by omitting the welding process, and can be applied to new fields.[6] **Figure 3** shows the expansion of the product line based on the El-λ balance. These three types of TS980 MPa grade ultra high-strength cold rolled steel sheets have a greatly improved El-λ balance in comparison with conventional materials. In general, because the hole expanding ratio of DP-type high-strength steel sheets tends to deteriorate when total elongation is increased, the relationship between these two properties is a trade-off. However, in JFE Steel's high λ-type TS980 MPa grade steel sheet, which is based on a DP microstructure, high stretch-flange formability equal to that of TS590 MPa grade cold rolled steel sheets is maintained, while also maintaining satisfactory elongation, by reducing the strength difference between the ferrite and martensite phases and optimizing the volume fraction of martensite. This balance of properties is attributed to fact that the hardness difference between the phases is reduced, preventing the initial formation of microvoids in the vicinity of the shearing edge during punching, and then preventing formation and coalescence of microvoids during stretch-flange forming (hole expanding), while an appropriate level of ductility is maintained by the presence of ferrite.[7,8] Absorbed energy during high strain rate deformation of steel sheets and parts increases with higher TS. On the other hand, at the same TS, it is known that steel sheets with a DP microstructure have high absorbed energy in comparison with sheets based on other hardening mechanisms.[9]

3.2 TS980 MPa Grade Ultra High-Strength Cold Rolled Steel Sheets for Mechanical Joining

The mechanical joining method is a method of mechanically joining multiple parts simultaneously in the forming process, and is beginning to be adopted in automobile parts because part manufacturing costs can be reduced by omitting the welding process, which is performed as a separate process.[10] The TOX joint developed by TOX PRESSO TECHNIK GmbH[11] is widely known as an example of mechanical joining. However, due to the high degree of forming of the joined parts in the mechanical joining method, high-strength steel sheets with poor formability are susceptible to cracking in formed parts, which reduces joint strength. For this reason, application of the mechanical joining method had been limited to low-strength materials such as mild steel and aluminum. JFE Steel carried out a basic study of the factors in the metal microstructure which control the occurrence of cracks in mechanical joints of high tensile strength steel and developed a TS980 MPa grade ultra high-strength cold rolled steel sheet which enables mechanical joining.

The material design concept of the developed steel is described below.

A detailed investigation of the occurrence of cracking in mechanical joints of high tensile strength steel revealed that this phenomenon shows no correlation with elongation in the tensile test, but shows a good correlation with the hole expanding ratio of steels with mechanical holes.[6] The hole expanding ratio of steels with mechanical holes is evaluated by performing the mechanical hole-punching process in the Japan Iron

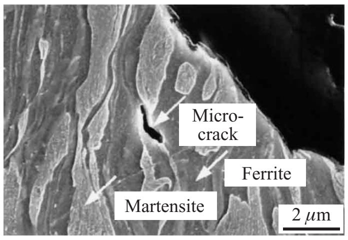

Photo 2 Cross-sectional microstructure of dual phase type steel at the mechanical joint

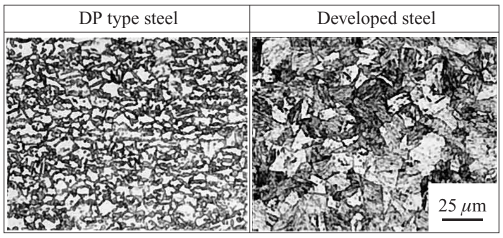

Photo 3 Optical micrographs of TS980 MPa grade steels

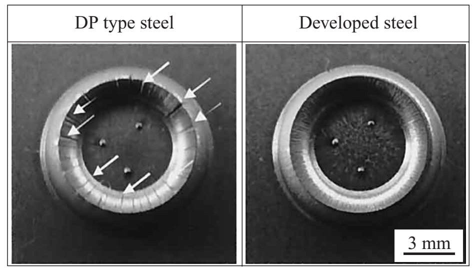

Photo 4 Surface appearance of the mechanical joint

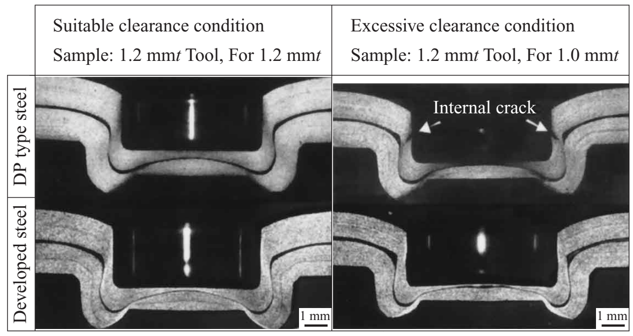

Photo 5 Cross section of mechanical joint

and Steel Federation Standard's hole expanding test (JFS T 1001-1996), and is known as an index for evaluating the local elongation of materials. Thus, it can be understood that improvement of local elongation is effective for improving cracking in mechanical joints.

An investigation of the cross section of the formed microstructure in the vicinity of a crack in a high λ-type TS980 MPa grade steel sheet with a DP microstructure (hereinafter called DP-type steel) in which cracking was observed found that cracking due to mechanical joining had originated at a microcrack at the interface between the ferrite and martensite phases, as shown in **Photo 2**. The occurrence of this microcrack was attributed to a difference in the degree of forming in the two phases, as the soft ferrite phase underwent greater elongation than the hard martensite. Assuming the inhomogeneous microstructure caused this reduction in local elongation, a homogeneous structure, including the micro level, was considered to be the optimum measure for improving mechanical joining performance. Accordingly, the goal with the developed steel was to realize a homogeneous microstructure by achieving a single martensite phase.

Photo 3 shows the microstructure of the developed steel in comparison with the DP-type steel. The DP-type steel has a microstructure of mixed ferrite and martensite, but in contrast, the developed steel consists of a single martensite phase.

Among the mechanical properties of the developed steel, the hole expanding ratio was an extremely good value of 100%, equivalent to that of TS340–440 MPa grade steel, as shown by the high λ-type TS980 MPa grade steel in Table 1.

Mechanical joining performance was evaluated using a test joining die with a punch diameter of 5.6 mm. **Photo 4** shows the appearance of the die-side sheet surface at the mechanical joint. In the DP-type steel, a radial cracking pattern can be observed, but in contrast, the developed steel is free of cracks and displays satisfactory appearance.

Photo 5 shows the cross sections of a mechanical joint made under the optimum joining conditions with a sheet thickness of 1.2 mm, and a joint made with an excessive tool clearance, with the sheet thickness reduced to 1.0 mm without changing the tool conditions. All steel sheets show satisfactory joint cross sections under the optimum joining conditions. When the clearance was excessive, the conventional steel showed an internal crack in the punch-side sheet, while the developed steel maintained a satisfactory cross section. In actual production processes, deviation in the tool clearance can be expected due to tool eccentricity, wear, and similar factors. Because joint strength is reduced if internal cracks occur,[12] materials with low cracking sensitivity are desirable. The developed steel is superior in stability of joint strength.

In spot welding, it is known that the fatigue strength of joints is independent of the material strength level and can be arranged on a single *S*-*N* curve, provided the nugget diameter is uniform. In contrast, with mechanical joints, the fatigue strength of the high-stress side is low, corresponding to static strength, whereas, on the contrary, the fatigue strength of the low-stress side is higher than that of spot welded joints. This shows that mechanical joints of the developed steel have fewer stress concentration than spot welded joints.[13]

4. Examples of Application of Developed Steels

Photo 6 shows an example of applications of the

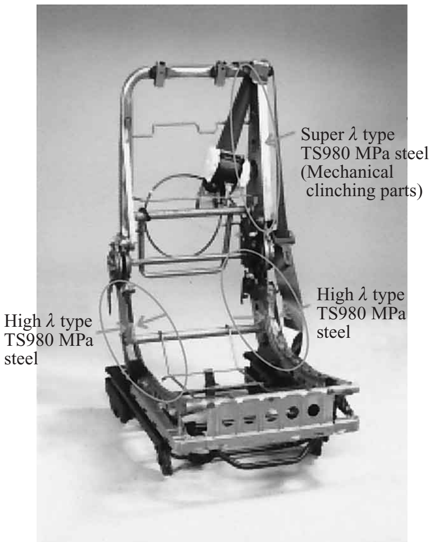

Photo 6 Automotive seat frame to which newly developed TS980 MPa steel sheets were applied

Photo 7 Applied example for center pillar reinforcement of TS980 MPa steel sheet (low YR type)(Formed by the experimental stamping tools in JFE Steel)

developed steels in automobile seat frame parts. The back side frame is a feature of this seat. Because super λ-type TS980 MPa steel was applied in this seat, a box structure could be formed from one sheet of material by bending, followed by mechanical joining. The newly-developed high λ-type TS980 MPa steel was applied in the cushion side frame parts.

Photo 7 shows the results of press-forming with experimental stamping tools simulating a center pillar outer using low YR-type TS980 MPa steel.

5. Conclusion

This paper has described the features and examples of application of JFE Steel's TS980 MPa grade ultra high-strength cold rolled steel sheets with excellent formability, which contribute to improved crashworthiness and weight reduction in recently developed automobiles.

(1) The developed steels form a line of products with excellent properties and features suited to individual applications, making it possible to satisfy diverse customer requirements.
(2) Super λ-type TS980 MPa grade steel for mechanical joining is contributing to improved safety, weight reduction, and cost reduction in automobiles by making it possible to adopt new seat designs and new joining methods.
(3) JFE Steel is committed to achieving further technical development while continuing to deepen its cooperative relationships with its customers, and to contributing to the development of safe, comfortable, people-friendly automobile bodies. Weight reductions made possible by JFE Steel's ultra high-strength steels are also contributing to improved fuel consumption as part of the solution to global environmental problems.

References

1) Yoshitake, A.; Iwase, K. Proc. of the 2000 Annual Meeting of JSAE/MMD, WS (2)-4, 2000.
2) Jitsukawa, M.; Hosoya, Y. NKK's state-of-the-arts flat-rolled products borne in a last decade. NKK Technical Report. no. 179, 2002, p. 36–44.
3) Yasuda, A.; Furukimi, O.; Seino, Y. Recent development and future of steel materials for automotive use. Kawasaki Steel Giho. vol. 32, no. 1, 2000, p. 1–6.
4) Sekita, T.; Kaneto, S.; Hasuno, S.; Sato, A.; Ogawa, T.; Ogura, K. Materials and technologies for automotive use. JFE Giho. no. 2, 2003, p. 1–16.
5) Nagataki, Y.; Tsuyama, S.; Hosoya, Y.; Kaneto, S.; Okuyama, T. Development of ultra high tensile strength steel sheets with tensile strength of 1 370 MPa and 1 560 MPa. Bull. of the Jpn. Inst. of Metals. vol. 32, no. 4, 1993, p. 238–240.
6) Hasegawa, K.; Urabe, T.; Yamazaki, Y.; Yoshitake, A.; Hosoya, Y. Development of 980 MPa grade ultra high tensile strength steel suitable for mechanical-clinching. Materia Jpn. vol. 42. no. 1, 2003, p. 76–78.
7) Nakamura, N.; Urabe, T.; Hosoya, Y.; Kaizu, T. Effects of microstructures on strech-flangeability of ultra high strengthened cold-rolled steel sheets. CAMP-ISIJ. vol. 13, 2000, p. 391–394.
8) Kawamura, K.; Hasegawa, K.; Urabe, T.; Hosoya, Y. Effect of microstructure on strech-flangeability in dual phase type cold-rolled high strength steel sheet. CAMP-ISIJ. vol. 15, 2002, p. 1229.
9) Shimizu, T.; Hira, T.; Iizuka, E. Impact energy absorbing capabilities and shape fixabilities of high strength steel sheets for automotive bodies. Kawasaki Steel Giho. vol. 32, no. 1, 2000, p. 14–20.
10) Liebig, von Hanns Peter; Bober, Jan; Mutschler, Jorg. VDI-Z. vol. 131, 1989, p. 95.
11) Bnder Bleche Rohre. 2000-09, p. 54.
12) Hasegawa, K.; Kawamura, K.; Urabe, T.; Hosoya, Y. SAE Technical Paper, 2001-01-3359.
13) NKK Corp. JP2002-161336 (A).