High Performance Steel Pipes and Tubes
Securing and Exploiting the Future Demands

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Wide variety of high performance steel pipes for infrastructure and automobile usages have been manufactured in UOE and ERW mills of Fukuyama and Keihin works for many years. High performance linepipes such as high strength corrosion resistance, high deformability structural pipes and ERW tubes suitable for hydoforming process have been developed for needs expected to come in near future. Characteristics of these steel pipes and some features of manufacturing process are introduced in this article.

1. Introduction

NKK has welded-pipe mills at Fukuyama and Keihin Works for the manufacture of UOE steel pipes, spiral steel pipes, electric-resistance welded pipes, and butt-welded steel pipes. Both production plants supply high-performance welded steel pipes that are used in infrastructure including linepipes, architecture and civil-use pipes, and in extensive areas including automobile component members.

This paper describes the characteristics of high performance UOE linepipes which were developed responding to the diversifying (conditions) of laying environments, of pipeline design and operational conditions. Those are high toughness, heavy wall and high corrosion resistant linepipes in addition to high strength linepipe. The increasing demand for the UOE linepipes is expected to continue. This paper also describes various types of steel pipes for architecture and civil field which were developed responding to diverse designs and to the need for high added value. Furthermore, this paper describes the high performance electric-resistance welded steel tubes developed by NKK for automobile component members using hydroforming technology.

2. High-performance linepipes

2.1 Diversification of laying and usage environments of pipelines and of design and operating conditions of pipelines

Gas and oil developments in cold areas and deep seas are steadily progressing. Accordingly, the laying and usage environment of pipelines and the properties of oil and natural gas transferred through the pipelines are also becoming more diversified.

Plans have been drawn up for laying a natural gas pipeline beginning from Korsakov of Sakhalin, passing through Tomakomai of Hokkaido, and entering Japan[1]. A 300km pipeline crossing the Black Sea at a depth of 2000m is under construction[2].

As a measure to reduce the cost of laying and operating a pipeline, the amount of steel is reduced by increasing the operating pressure or by applying high-strength linepipes. A comparative study was conducted on linepipes of various grades[3]. According to the results, a total cost reduction of about 5% is expected by upgrading from X65 to X80 and about 8% by upgrading to X100.

For further cost reduction, the fit-for-purpose pipeline design, including the selection of use materials, has recently drawn attention, and evaluation methods applicable under conditions closer to the actual environment have been introduced. For example, the "Requirement guidelines for carbon steels used in hydrogen sulfide environment" of Document No.16 of the EFC (European Federation of Corrosion) provides a testing solution used in a simulated well environment[4], complementing the widely-used Solution A and Solution B of NACE TM0175-96.

2.2 Manufacturing technology of steel pipes with high strength and high toughness

The manufacturing of high-strength pipelines should emphasize low temperature toughness from the viewpoint of safety, and excellent field weldability from the viewpoint of efficiency in girth welding. These characteristics, however, conflict with the strengthening of steel. To resolve the conflict, high strength pipelines are manufactured by the processes of controlled rolling and accelerated cooling. The accelerated cooling process, which cools the steel plates on-line after controlled rolling, was commercialized at the Fukuyama Thick Sheet Plant of NKK in 1980 for the first time in the world[5]. Application of accelerated cooling allows the manufacture of high-strength sheets with superior toughness using steels with lean materials toughness. Furthermore, NKK developed a new accelerated cooling system, the "*Super*-OLAC," having features of high cooling speed, precise temperature control, symmetric cooling on top and bottom surfaces, and minimal temperature scattering in an accelerated cooled plate. The "*Super*-OLAC" entered operations in 1998, and achieved a high cumulative production rate of over 1.5 million tons within only three years.

Up to grade X65 of sour resistant linepipes were developed and brought into practical use by end of the 1980s. Key technologies of the development are the reduction in sulfur and phosphorus, the shape control of sulfides using calcium, continuous casting and optimizing of controlled rolling and accelerated cooling conditions. To increase sour-resistance performance, NKK has established a process for improving cleanliness through the reduction in oxygen content in steel before deoxidation[6]. Furthermore, with the objective of manufacturing sour-resistant steels and high-strength linepipe steels which contain a small amount of carbon and which require cleanliness, NKK has developed the zero-slag process. This process, which applies low-silicon hot metal to a hot-metal preliminary treatment furnace, reduces costs and improves the purity of steel[7].

In addition, to meet increasingly strict and diverse demands for quality, the automatic ultrasonic inspection system for weld seams of UOE pipes was renewed in 1999. The system has two manipulators that can use a maximum of 20 channel probes simultaneously and a highly accurate seam-tracking sensor.

Due to the increasing severity of dimensional accuracy, NKK has promoted the forming technology to optimize the C-formed shape. For attaining thicker-walled pipe and an ideal C-form shape, the C-shape press is to be replaced in order to expand the manufacturing range.

2.3 Next-generation high-performance linepipes

Next-generation high-performance linepipes were developed in response to the above-mentioned diversifying laying environment and the need for reducing the cost of the linepipes, and demand for the linepipes is expected to increase.

2.3.1 High-strength linepipes

In 1991, for the first time in Japan, NKK manufactured X80 linepipes, which were delivered to Canada. Subsequently, NKK has manufactured about 50 thousand tons of X80 linepipes. **Fig.1** shows the statistical data of Charpy absorbed energy of X80 linepipes as an example of their mechanical characteristics. As seen in the figure, average absorbed energy reaches as high as around 250J (-5℃) in spite of the high strength of X80. The average value fully satisfies the specifications of ISO for the energy necessary to arrest propagation of unstable ductile fracture of X80 linepipes.

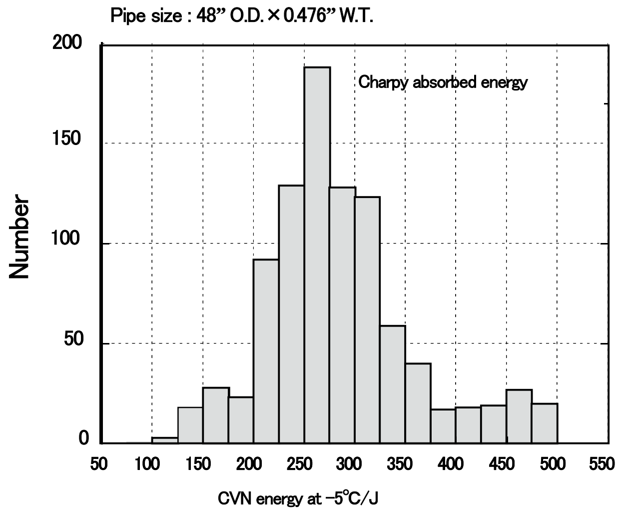

Fig.1 Charpy absorbed energy statistical data of X80 linepipe mass-produced in NKK

NKK also promotes development study on X100 linepipes. Joint studies in Western countries focus on the application of high-strength materials, such as X100 pipes, and NKK also conducts studies to establish an evaluation method and required performance standards for X100 linepipes by supplying samples to the joint study groups.

As an example of investigated methods for evaluating X100 linepipe strength, **Fig.2** compares the stress-strain relation between two kinds of tensile tests and a full-scale pressurized test. For a high-strength material such as X100 linepipe, the Bauschinger effect is significant for flattening the specimen. Consequently, the test results obtained from currently used API flattened specimens give significantly low values compared with the test results of the full-scale pressurized test.

The manufacture and supply system for X80 linepipes that have satisfactory mechanical properties and on-site weldability has already been established. The most recently advanced X80 Schluchten-Werne (Rhgas) project and NGTL (TCPL) project have an extended laying distance of 260km and 250km, respectively. The development of bend pipes and fittings for the X80 linepipes is somewhat delayed; however, NKK has almost completed the development of induction-bent pipes up to X80[8]. Current issues for the X100 linepipes include the development of bend pipes and circumferential welded materials, and of adequate welding processes. The development of these peripheral technologies and the study of the above-described ductile fracture behavior should further expand the application fields of X80 and X100 linepipes.

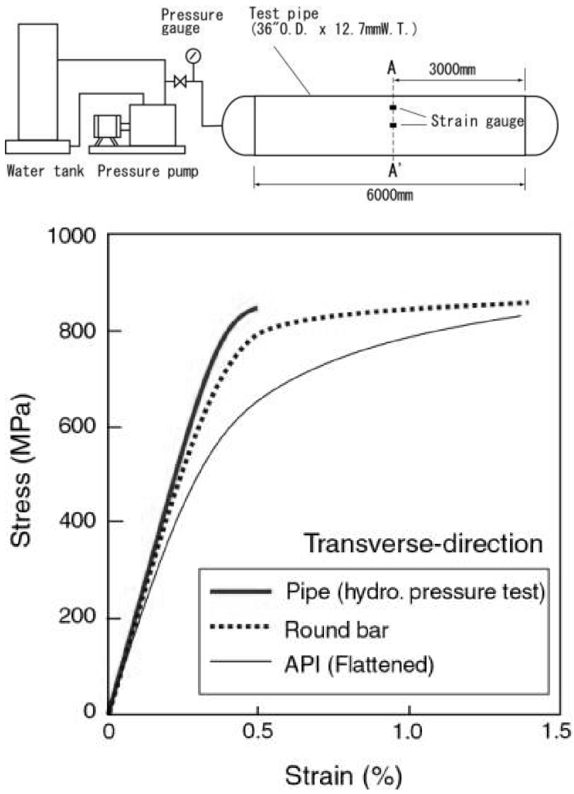

Fig.2 Comparison of stress strain relationships measured by small scale and full scale testing

2.3.2 Heavy-wall linepipes

In deep-sea pipeline systems, steel pipes having heavy walls are necessary to avoid pipe collapse under external pressure and by buckling likely to occur during laying works. For a 300km pipeline crossing the Black Sea at a depth of 2000m, the applied pipes have a 5% or higher ratio of wall thickness to pipe diameter (t/D), and the pipe grade is as high as X65. Manufacturing steel pipes with heavy walls requires optimum conditions for the controlled rolling and accelerated cooling processes to attain high strength and high toughness (DWTT characteristics). The application of high cooling speed by "*Super*-OLAC" is effective for linepipes with heavy walls, and also gives superior DWTT characteristics to those of conventional materials, as shown in **Fig.3**.

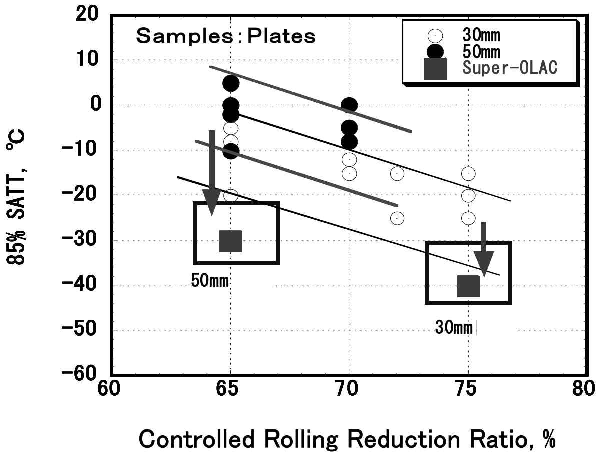

Fig.3 Toughness (DWTT) improvements achieved by applying "*Super*-OLAC"

In this project, buckle-arrestor pipes having a wall thickness of 52.7mm were adopted to prevent propagation of buckling during pipeline laying works. In addition to the heavy-wall pipes, NKK developed and manufactured the buckle-arrestors. As an example of the mechanical properties of heavy-wall steel pipes, **Fig.4** shows statistical data of tensile strength in circumferential direction of the pipes. As seen in the figure, sufficient strength is attained even with a pipe having 52.7mm of wall thickness. Furthermore, the difference in tensile strength between the maximum and minimum values is as small as about 50MPa.

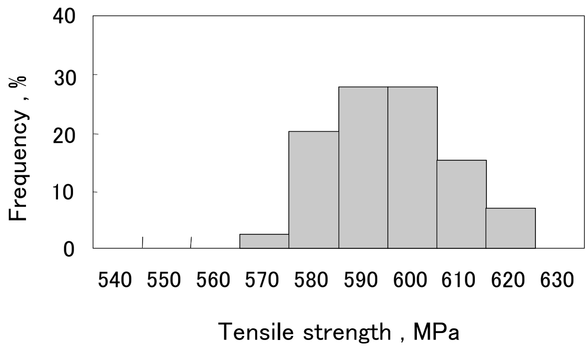

Fig.4 Tensile strength statistical data of heavy wall linepipe mass-produced in NKK

2.3.3 Fit-for-purpose linepipes

As previously described, the requirement for adequate, but inexpensive, steel materials will increase, with the objective of reducing pipeline system cost. That is, the method of selecting adequate materials by testing under conditions reflecting the actual environment is more likely to be adopted than selecting expensive and excessively high-quality steel materials by conducting evaluation tests under severe conditions. On this basis, the scope of application of linepipes which are suitable in H_2S concentration or in high pH environments, and weldable 13Cr steel is expected to increase.

As described above, EFC proposes an SSC test under conditions closely matching the actual environment, thereby preventing cost increases due to the selection of excessively high-quality steel materials. The selection of adequate steel material is presently being investigated by identifying the composition and hardness of steels applicable for all levels of hydrogen sulfide concentrations and pH values. **Fig.5** shows examples of such study results, i.e. the critical hardness for crack generation increases to around 280 Hv in a low H_2S concentration of 80%CO_2-20%H_2S. In addition, the critical hardness increases caused by the increase in pH value. On the basis of these study results, easing of the required critical hardness would reduce the linepipe manufacturing cost.

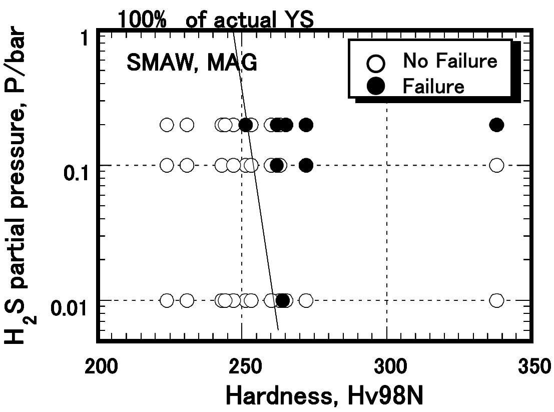

Fig.5 Effect of H_2S content on the SSC

2.3.4 NK-HIPER, an anti-seismic and deformable linepipe

In addition to high strength and superior toughness, seismic resistance and deformability are other indispensable properties of linepipes running in Japan where large earthquakes are frequent. The design of domestic pipelines is based on the "Seismic design codes for high-pressure buried pipelines"[9]. A review work on the anti-seismic design of pipelines is underway based on the Hyogo-ken Nambu Earthquake disaster of 1995. The new anti-seismic design will adopt an advanced inelastic design method that can withstand large earthquakes equivalent to the Hyogo-ken Nambu Earthquake, with improved deformability of the steel pipes. The Guideline of Anti-seismic Design of Gas Pipelines specifies a design formula for inelastic buckling strain of steel pipes that is proportional to the pipe wall thickness and inversely proportional to the pipe diameter. In a linepipe with increased strength, the reduced wall thickness increases the ratio of pipe diameter to wall thickness, as shown in **Fig.6** (ordinary material), which decreases the critical buckling strain. NKK has conducted investigations on improving the buckling strain induced in high-strength linepipes, and has developed "NK-HIPER", an anti-seismic linepipe that has 1.5 times or more inelastic buckling strain in uni-axial compression mode than ordinary pipes. The high buckling performance of NK-HIPER is attained by improving the work-hardening performance of the steel. **Fig.6** compares the anti-buckling performance between NK-HIPER and an ordinary material. The high-strength linepipe material design used in the Sakhalin pipeline that crosses Japan could require anti-seismic and deformable properties. Recently, NKK began commercial production for domestic applications, and intends to supply the products for pipelines that require high deformability.

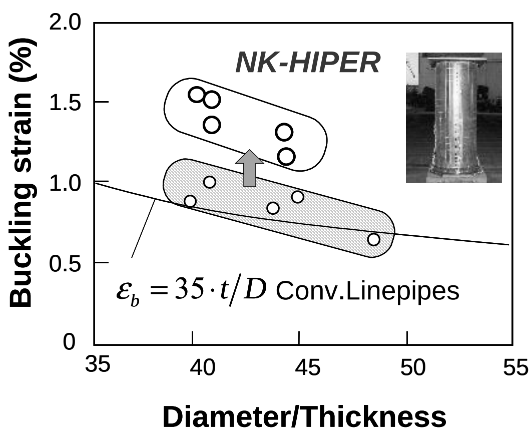

Fig.6 Buckling strain versus diameter to thickness ratio in standard gas pipelines and "NK-HIPER"

3. Steel pipes for infrastructure

Due to the excellent structural strength of circular steel pipe columns and the superior decorative appearance in the architecture field, the large-diameter welded steel pipes have been increasingly adopted in the infrastructure. From the beginning of the 1990s, NKK has promoted the application development of welded steel pipes in these fields, and successively developed and commercialized the "NT Column" in the architecture field, the "Tsubasa Pile, a screw steel pipe pile with tow wing", "pipes with ribs", the "NKK EAGLE, a net supporting pillar", and the "NK Pillar" in the civil field.

The NT Column is a UOE steel pipe or a press-bent steel pipe with external ring diaphragms that are unified by automated welding. The NT Column is less expensive than conventional type columns and is also easily applied to concrete-filled columns (CFT). The Fukuyama UOE mill started operations of a building materials working plant in 1997 to conduct mounting of diaphragms to the NT Column. The development of the NT Column began in 1991, after which NKK increased the size of the NT Column (increased in wall thickness) and improved the tensile strength and performance. As a result, the plant can produce a STKN590 grade that has a low yield ratio (85% or less) and high toughness. **Fig.7** shows the manufacturing results of the NT Column of STKN490 N/mm^2 class, which were manufactured to order. The manufacturing was conducted in a region of $0.02 \leq t/D \leq 0.13$, applying UOE, cold press bending + SR or hot press bending. The tensile characteristics assure adequate strength satisfying the condition of YR ≤ 80%. For toughness, the Charpy absorbed energy at 0℃ is sufficiently above 27J for both the base material and the welded joint. Thus, NKK established the production technology of the NT Column, a building-structure high-performance steel pipe having stable low-yield ratio and high toughness and started mass production for extensive application in buildings and civil structures.

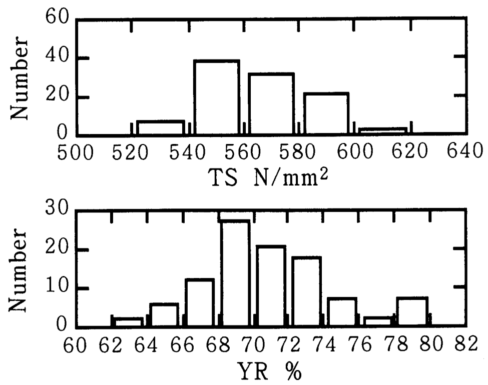

Fig.7 Strength statistical data of "NT Column" mass-produced in NKK

4. High formability electric-resistance welded steel tubes for hydroforming

4.1 Hydroforming technology and application to automobile component members

Hydroforming is a technology for the unified forming of complex-shaped tubular parts. A steel tube is placed in a die, and the steel is filled with water, after which hydraulic pressure is applied to the water to form the steel tube. From the latter half of the 1990s, application of the technology to electric-resistance welded steel tubes for automobile component members has gradually increased inside and outside Japan[10]. Particularly in Japan, maximizing the effect of weight reduction and increased rigidity by applying steel tubes, requires higher strength and higher formability of base materials. As a result, high formability electric-resistance welded steel tubes applicable to these uses are in demand in Japan.

In response, NKK has developed 290 to 590MPa class steel tubes with excellent formability for hydroforming, which are described below.

4.2 High formability electric-resistance welded steel tubes for hydroforming

The members formed from steel tubes by hydroforming are generally subjected to complex strain such as roll forming, pre-forming (such as bending and die pressing), and bulge forming, compared with members that are formed from steel sheets by a continuous press-forming line. Therefore, to secure the formability necessary in forming stages such as bending and bulge forming, it is important to apply the materials design inherent to the steel tube. The result minimizes the degradation of formability caused by strain, as well as maximizing the formability of the base steel sheet before roll forming.

Fig.8 shows the relation between tensile strength TS, yield ratio YR, uniform elongation U-El, total elongation El, and n value for electric-resistance welded steel tubes prepared from steel sheets having the aging index A.I. < 10MPa. An electric-resistance welded steel tube having A.I. < 10MPa shows lower YR, and higher U-El, El, and n value than those of a comparative tube having A.I. ≥ 20MPa. The superior formability is presumably due to the level of A.I. < 10MPa (called non-aging), which prevents the degradation of formability under strain (mainly solid solution N enhances the degradation). The basic materials design of NKK for high formability electric-resistance welded steel tubes for hydroforming adopts the control of the above-described composition and hot rolling condition to assure A.I. < 10MPa on the base steel sheets. At the state of hot-rolled base material steel sheets, no effects of the A.I. level on the tensile characteristics appear.

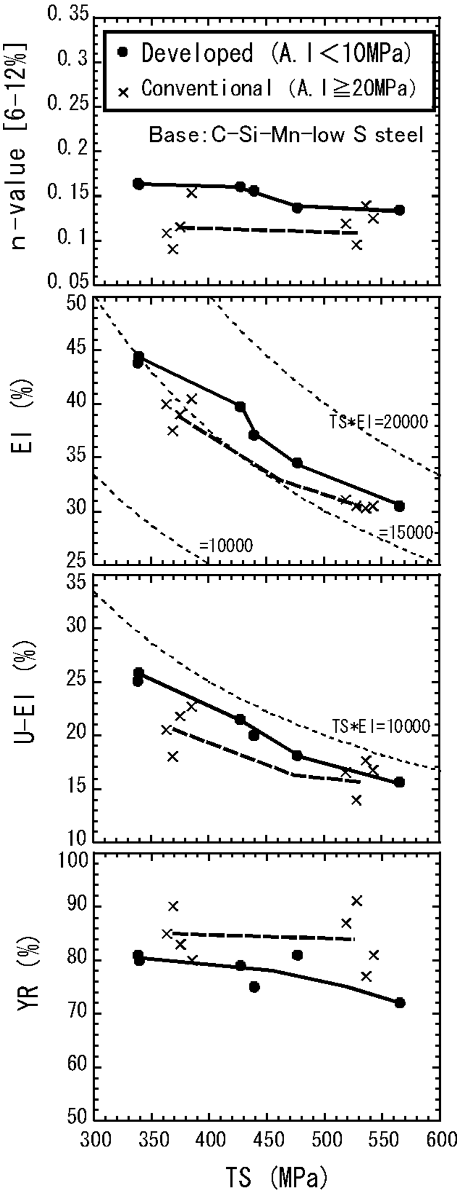

Fig.8 Relationship between tensile strength and the tensile properties of developed and conventional tubes (t/D=2～4%; JIS No.12A)

Fig.9 shows the relation between TS and the maximum expanding ratio on bulge forming of steel tubes in a rectangular die having a circumferential increase of 20%. The high formability electric-resistance welded steel tubes for hydroforming, prepared by suppressing the degradation in formability caused by strain, produced a rectangular shape having a circumferential increase of 20% without fracture independent of strength. On the other hand, comparative tubes having A.I. ≥ 20MPa generated fracture during forming.

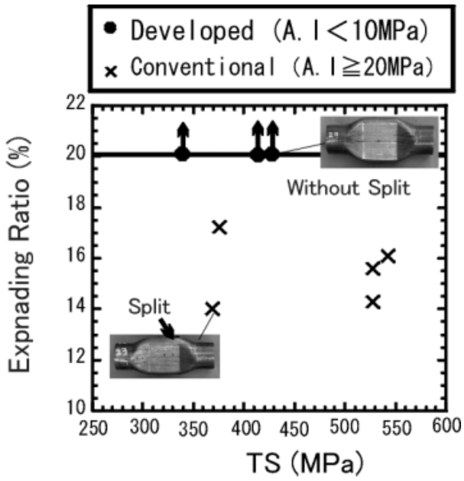

Fig.9 Relationship between the tensile strength and the hydroformability in rectangular die cavity (Maximum expanding ratio = 20%)

Fig.10 shows the strain and the forming limit for high formability electric-resistance welded steel tubes for hydroforming observed during free-bulging under varying ratios of axial stress to circumferential stress, α m[11)] , of the nominal stress applied to the tubes. Increased axial force (decrease in α m) increases the critical circumferential forming limit, and a high forming limit exceeding the circumferential increase rate of 60% is attained under the condition of α m = -0.5.

As described above, the high formability electric-resistance welded steel tubes for hydroforming on the non-aging base manufactured by NKK show excellent bulge formability, and superior secondary forming, including bending.

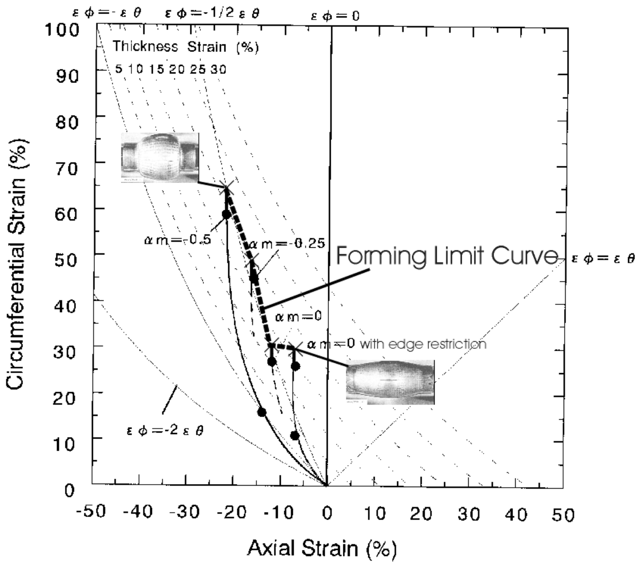

Fig.10 Forming limit curve of the developed tube (TS=340MPa) in free-bulge

Fig.11 shows the hardness distribution near the weld seam on a high formability electric-resistance welded steel tube for hydroforming made by NKK. Every manufacturing line of electric-resistance welded tubes at NKK has a high power post-annealer after the electric-resistance welding, which is able to heat-treat the welded section in line. Accordingly, the steel tubes have no hard portions generated from heating and cooling during the electric-resistance welding. As a result, the electric-resistance welded steel tubes require fewer countermeasures to mal-forming than comparable steel tubes, thus offering advantages for component member design and process design.

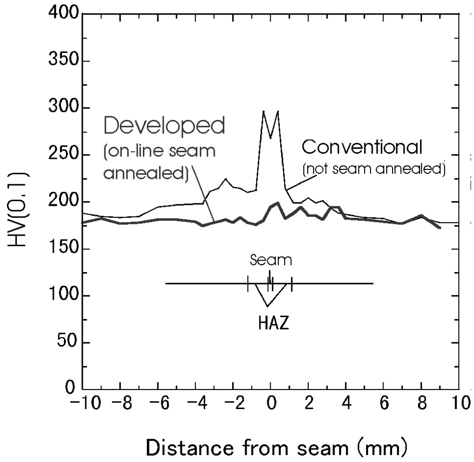

Fig.11 Hardness distribution in weld seam of the developed tube with on-line seam annealed compared with the conventional tube (TS=490MPa)

In actual hydroforming, formability is significantly affected by a large number of variables other than the material properties: i.e. pre-forming, strain distribution induced by die restriction, lubrication, strain gradient depending on die shape, and axial force. Particularly for a high-strength material that is difficult to form, it is essential to combine an optimum base material, forming technology, and forming conditions. On this basis, in addition to the above-described materials technology, NKK has extensively studied forming technology (hydroforming technology and steel tube secondary forming technology) and numerical analysis technology[11], and has established an integrated system from development to mass production of hydroforming parts of automobile-use steel tubes, also covering prototyping technology including the die design.

5. Conclusion

In the UOE linepipe field, the development of high-strength and high-toughness materials will lead to new materials development driven by diversifying design, operating conditions, evaluation methods and cost reduction.

This paper described the high strength and high toughness of linepipes (X80 to X100, heavy wall, sour-resistant, “NK-HIPER”) developed by NKK in response to next-generation requirements. We believe that these products will be widely used in next-generation pipelines and those materials suitable to environments should continue to be developed.

As for the high formability electric-resistance welded steel tubes for hydroforming, NKK is continuing development work on base materials technology, forming technology, and numerical analysis technology to meet the demand for high-strength materials exceeding a 590MPa level. In addition to formability, the importance of base materials technology, component member shapes and forming-process design technology that takes into account product characteristics such as impact and fatigue, should be emphasized.

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