Leading High Performance Steel Plates with Advanced Manufacturing Technologies

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Recent development of construction and design technology gives larger and heavier steel structures. In addition, reductions of construction and maintenance cost are also recently focused in various fields. From this viewpoint, higher strength, better weldability and higher performance are required for structural steels. In order to achieve these requirements, advanced and sophisticated process technology is critical in addition to precise material design. This paper describes the development of the Super-OLAC (On Line Accelerated Cooling) and its various products.

1. Introduction

The performance required in steel plates in recent years has differed to some extent by field of application. However, progress in the design and construction technologies used in final products and structures, as well as demand for total cost reduction, has become increasingly intense. In concrete terms, diverse properties are now required in structural steels, including higher strength, improved weldability, and higher performance. Both precise material design technology and advanced process technology are essential for satisfying these performance requirements.

From this viewpoint, NKK Corporation recently developed and applied a completely new on-line accelerated cooling process called *Super*-OLAC® (On-Line Accelerated Cooling). This paper briefly describes the development of *Super*-OLAC, together with the development and features of new high performance steel plates produced using this technology.

2. Development of *Super*-OLAC

The key elements in the technology known as accelerated cooling are controlled rolling and TMCP (Thermo Mechanical Control Process)[1]. NKK Corporation undertook the development of accelerated cooling technology in advance of other steel makers, and in 1980, succeeded in applying an on-line accelerated cooling process for plates called OLAC in a practical manufacturing operation for the first time in the world[2].

The first OLAC process was installed between the finishing mill and leveler at the company's Fukuyama Plate Mill and employed simultaneous type cooling equipment (**Table 1**). In this method, microstructure control was performed in the rolling process, and plates were held up and cooled while being oscillated at the OLAC. Top side cooling was performed by a round-pipe laminar system which dropped columns of cooling water onto the plate. A spray cooling method was adopted for the bottom side using spray nozzles arranged between the table rolls[2].

Table 1 List of OLAC application in NKK plate mills

Name	OLAC	OLAC II	*Super* - OLAC
Works	Fukuyama	Keihin	Fukuyama
Establishment	1980 (Removed when *Super* -OLAC was installed)	1985	1998
Cooling type	Simultaneous	Progressive	Progressive
Length (m)	44	20	20
Distance from FM *) (m)	24	53	68
Top	Pipe laminar	Curtain laminar	Corridor flow
Bottom	Spray	Suction laminar	Close suction laminar
Number of zones	-	12	22

*)FM : finishing mill

In 1985, the second OLAC unit, OLAC II, was installed at NKK's Keihin Works Plate Mill. OLAC II uses progressive type cooling equipment which performs cooling while the plate is traveling. A flat laminar cooling system, which drops a curtain-like laminar flow of cooling water on the plate, was adopted for top side cooling. For the bottom side, suction laminar cooling using a water spray with conduit pipes was adopted. This method improves the cooling function by ensuring that the water in the water tank is entrained with the moving plate. The startup of OLAC II established a supply system for accelerated cooling (TMCP) plates at both of NKK's main works, Keihin and Fukuyama.

By the beginning of the 1990s, mass production technology was required to meet rising demand for TMCP plates. A key element in this technology was more uniform cooling, aimed at minimizing the cooling strain which typically occurred with the conventional method, and thereby reducing plate re-leveling work. At the same time, product quality requirements also became stricter, as seen in the increasing need for plates with reduced strength deviations or with a narrower target strength range. Hence, improved accuracy was also desired in the cooling finishing temperature in accelerated cooling. In responding to these needs, NKK carried out basic research on cooling, which resulted in the development of a next-generation accelerated cooling process called *Super*-OLAC (**Photo 1**) based on an unprecedented, completely new concept. A commercial *Super*-OLAC process was put into operation at Fukuyama Works in 1998[3].

Photo 1 *Super*-OLAC at Fukuyama Works

Broadly classified, two forms of heat transfer phenomena and boiling occur when a heavy steel product is water-cooled (**Fig.1**). These are nucleate boiling, which occurs when direct cooling water comes into contact with the material and heat is transmitted by generation of air bubbles, and film boiling, in which a film of steam is formed between the material and the cooling water, and heat is transmitted through this steam film. The cooling capacity of nucleate boiling is the higher of the two types.

In considering the accelerated cooling process for steel plates, at the start of cooling, the surface temperature of the plate is high and cooling proceeds in the film boiling condition. However, as the surface temperature decreases, the steam film becomes unstable and local contact begins to occur between the cooling water and steel plate. Boiling then shifts gradually to the nucleate type, passing through a transition boiling phase in which nucleate boiling coexists with film boiling. Because the cooling capacity characteristically increases as cooling proceeds, cooling is unstable in this transition phase.

In conventional accelerated cooling, the top side cooling water remains on the plate until evaporation is complete, causing secondary cooling over an extensive area. This type of secondary cooling due to residual water on the top side was a serious problem, as the cooling mode tended to shift to the unstable transition boiling condition, which increased local temperature deviations accompanying cooling and resulted in non-uniform cooling of the finished plate.

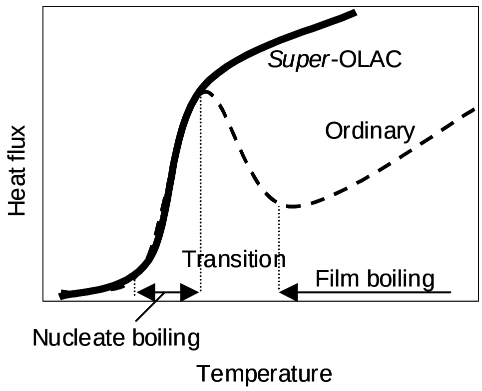

Fig.1 Boiling curve of *Super*-OLAC

To solve this problem, NKK investigated a cooling method which would secure nucleate boiling over the entire plate surface almost simultaneously with the start of cooling, thus avoiding the transition boiling phase. This resulted in the adoption of a top side cooling method in which cooling is performed by a uni-directional "corridor" flow of cooling water in the direction of plate transportation, from nozzles located in close proximity to the plate (new water flow controlled cooling method), and a bottom side cooling method in which water is sprayed from a high-density arrangement of nozzles in the water tank and cooling is performed by the accompanying flow of water traveling with the plate (spray cooling with high-density conduit system). Unbalanced top and bottom side cooling was a concern due to the asymmetrical top-and-bottom design of the cooling system. However, in actual practice, top and bottom side cooling is uniform because the new technology realizes high cooling capacity nucleate boiling on both sides of the plate, achieving a rapid cooling condition in which heat diffusion from the plate interior is rate-governing. This means that the cooling rate at the plate center of thickness can be decided immediately from the plate thickness (**Fig.2**). It is also possible to obtain a uniform surface temperature distribution in plates after the *Super*-OLAC process, identical to that of as-rolled materials which are not given accelerated cooling.

A variety of new products have been developed taking advantage of the superior cooling uniformity and high cooling capacity of the *Super*-OLAC process. To date, these include YP40kg steel for container ships, which enables one-pass welding with ultra-high heat inputs, linepipe (NK-HIPER) with greatly improved earthquake resistance performance in comparison with conventional steel pipes, and steel plates for sour linepipe service (X65), in which strength deviations have been absolutely minimized to a standard deviation (σ) of 9 MPa. Cumulative production of TMCP plates using the *Super*-OLAC in the three years since startup has now reached approximately 1.5 million tons.

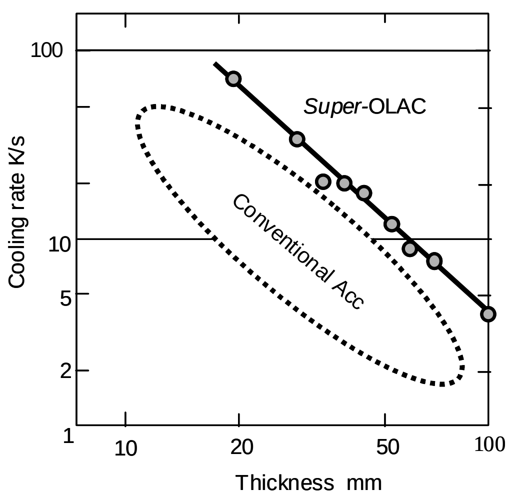

Fig.2 Cooling rate of *Super*-OLAC

3. Heavy steel products for shipbuilding

3.1 High tensile strength steel for ultra-high heat input welding for large container ship use

Because container ships are constructed without bulkheads in the hold and have large openings in the deck, the structure is designed to secure the strength of the vessel as a whole by using heavy gage, high strength steel plates in the upper side walls of the hull. The recent trend toward large-scale container ships has resulted in progressive adoption of heavier gage and higher strength steel products. For example, in large vessels exceeding 6000 TEU, shipbuilders are beginning use steel plates with a maximum thickness of 65mm and yield strength of 390N/mm^2. Heavy gage plates of this type can be welded in one pass using high efficiency electro gas arc welding, but an ultra-high heat input on the order of 400～500kJ/cm is required. Heat inputs of this level cause coarsening of the microstructure in the HAZ (Heat Affected Zone), making it difficult to secure low temperature toughness. Furthermore, it is also necessary to increase the Ceq (Carbon equivalent) with heavy gage and high strength plates, but this reduces weldability and HAZ toughness. Considering these problems, a manufacturing technology for high strength and heavy gage materials, using a composition system with reduced Ceq, was required.

An NKK technology for improving toughness (NK-HIWEL) by reducing the content of free nitrogen, which deteriorates HAZ toughness, had been used for some time with the company's steel products for high heat input welding (YP:～355N/mm^2, heat input:～200kJ/mm). To cope with further increases in material thickness (plate thickness:～65mm), higher strength (YP:～390N/mm^2), and ultra-high heat input welding (heat input: ～500kM/cm), in the present steels for ultra-high heat input welding for large-scale container ship use, the microstructure of the HAZ is refined by applying a micro-alloying technology which enables control of the microstructure during ultra-high heat input welding, substantially improving HAZ toughness. Using the *Super*-OLAC technology described above in the manufacture of this plate, it was possible to produce high strength steel plates with a maximum thickness of 65mm and YP of 390N/mm^2 with no loss in weldability at the same Ceq level as the conventional steel. As a result, satisfactory HAZ toughness is secured even at temperatures as low as -40℃, as shown in **Fig.3**, making it possible to apply ultra-high heat input welding with E grade shipbuilding plates. The newly developed steel has won an excellent evaluation from customers, and orders in excess of 10000 tons have already been produced for large container ships for use on trunk routes, including North American and European sea lanes and others.

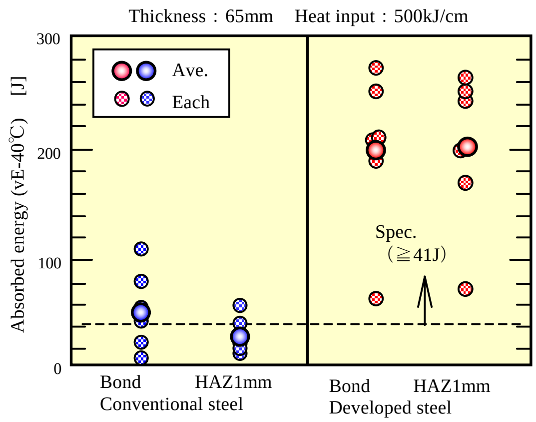

Fig.3 Toughness of SEGARC welded joints

3.2 High corrosion resistance plates for crude oil tanker deck plate use

In the cargo tanks of crude oil tankers, corrosion of the under side of the deck plates is an important factor limiting the service life of vessels. Based on a wealth of accumulated know-how in the field of corrosion-resistant steels, NKK carried out systematic research on the effect of alloying elements and strengthening of the function of the shop primer in preventing corrosion of steel plates for crude oil tanker deck plate use. As a result, the optimum composition balance design, using TMCP technology in combination with small additions of special alloying elements, was found to be effective in extending the corrosion protection life of the shop primer by approximately two times, while also reducing plate corrosion. Furthermore, application of a TMCP technology which includes the above-mentioned *Super*-OLAC in the manufacture of these plates made it possible to produce not only soft steel grades (YP: 235N/mm^2 class), as would be expected, but also high tensile strength steels (YP: 315, 355N/mm^2 class) with the same Ceq as at present. Using this combination of technologies, a steel plate for deck plate use, NAC5, was developed and commercialized. The new product possesses weldability equal to that of the conventional steel, together with substantially improved corrosion resistance, while minimizing cost increases. In addition to extending the useful life of deck plates (NKK's estimate: approximately 5 years), application of NAC5 to crude oil tanker deck plates makes it possible to reduce the maintenance costs required in ship repair dock work by half. As a further advantage, by alleviating corrosion of tank deck plates, the new product also reduces contamination in cargo tanks by iron rust, and thus can be expected to protect unloading pumps.

The features of the newly developed steel, NAC5, are summarized below.

- When used in combination with shop primer, NAC5 suppresses corrosion of crude oil tank deck plates, thereby extending the useful life of the vessel.
- Because NAC5 possesses weldability equivalent to that of the existing steels, it is possible to use existing welding materials. Corrosion resistance equal to that of the base material is secured in welds.
- NAC5 offers excellent economic performance, providing the maximum benefit at the minimum cost increase.

Thus, high expectations are placed on NAC5 as a material which not only reduces ship construction and maintenance costs, but also satisfies the requirements of both improved deck plate reliability and good weldability.

4. Heavy steel products for bridges

4.1 Weathering steels for coastal environments

In response to the public need for cost reduction by extending the life cycle of outdoor steel structures, beginning with bridges, NKK is developing a series of "Weathering Steels for Saline Coastal Areas", which can be applied even in coastal regions where the conventional weathering steels could not be used due to the high concentration of salt in the air. These newly developed steels not only provide dramatically improved atmospheric corrosion resistance, but also excellent weldability.

The features of the developed steels, CUPLOY 400-CL, CUPTEN 490, and CUPTEN 570-CL, are described below.

- Because a dense layer of fine rust is formed on the plate surface, the developed steels possess excellent atmospheric corrosion resistance and can be used in an unpainted condition, even in coastal environments with high concentrations of airborne salinity (0.05mmd～0.40mmd).
- Initial period rust streaks, which occur before the protective rust layer forms, are slight, giving the structure satisfactory appearance as part of the scenic environment.
- Mechanical properties are consistent with those of atmospheric corrosion resistant steel SMA in JIS G 3114.
- Weldability and other construction-related features are satisfactory.

The results of an exposure test at Miyakojima Island showed that these steels provide excellent atmospheric corrosion resistance, even with a low-Ni composition system, thanks to their optimum alloy design. Because these products also offer superior economy, use is expected to expand to a variety of applications in the future, centering on bridges.

4.2 Rust stabilizer for weathering steels, CUPTEN COAT M

Demand for weathering steels has increased in recent years in response to the heightened need for life cycle cost reduction in bridges and other steel structures. However, degradation of the scenic environment by rust streaks which occur before a stable rust layer forms and related types of pollution had become a problem. Although various rust stabilization treatments can be used to prevent rust streaks on weathering steels, the conventional methods had various problems, including the following:

- Multi-coat painting and/or special chemical conversion treatment was necessary, resulting in a complicated and expensive work process.
- Chrome compounds and similar substances were used, placing a heavy load on the environment.

In contrast, CUPTEN COAT M, which was developed by NKK, is a revolutionary rust stabilizer with the following advantages:

- As a single-layer (one-coat) treatment, CUPTEN COAT M has excellent use-related features. With NKK's proprietary technology, it is possible to combine all the functions necessary for rust stabilization (stable rust maturing, rust streak prevention, salinity permeation prevention) in a single-layer paint film, realizing a simple, easy work process.
- The new rust stabilizer is completely free of chrome and lead compounds, realizing excellent environment-friendliness, including long-term preservation of the scenic environment.
- NKK's lineup of heavy steel products also includes pre-coated steel plates with CUPTEN COAT M, making it possible to apply new fabrication processes which omit the user's product blast process, further reducing the cost of construction.

These advantages of CUPTEN COAT M have been highly evaluated by users. As a result, the new product has already been applied in numerous projects and, in the future, is expected to respond to the diverse needs of customers in fabricating more rational steel structures.

5 Heavy steel products for building and construction use

5.1 High weldability 590N/mm^2 class steel plates for building and construction use

High performance 590N/mm^2 class high tensile strength steel was developed by NKK Corporation in advance of other steel makers worldwide. This material is already used in box columns of buildings and similar applications, and technical guidelines for its use have been established as part of the Comprehensive Technical Development Project of Japan's Ministry of Construction. By adopting the optimum composition design and applying a special heat treatment process, while continuing to give consideration to weldability, it was possible to reduce the yield ratio of the developed steel to 80% or less, which is important from the viewpoint of earthquake resistance. This steel received the 1992 Okuchi Memorial Technology Prize and was granted general approval by the Minister of Construction in 1996. Under the designation NKK-SA440, orders for 15 structures totaling approximately 10000 tons have already been received and produced. However, in comparison with 490N/mm^2 class steel, the high strength of the conventional SA440 steel had placed numerous restrictions on its use, including the preheating temperature, bead length, etc., when performing welding, and these problems required improvement.

Against this background, NKK developed NKK-SA440B-U and NKK-SA440C-U, which inherit the excellent properties possessed by the existing steel (high strength, earthquake resistance, high toughness), while achieving a dramatic improvement in weldability by reducing Ceq to approximately 2/3 the conventional level. The developed steel has the following advantages in comparison with the conventional material.

- Changes in material properties at butt welds and fitting mounting areas are slight.
- Changes in material properties due to local heating are slight.
- The weld bead length in assembly welding (tack welding) can be shortened.
- The preheating temperature can be reduced or preheating work can be omitted.

The newly developed steel won high marks not only from steel frame fabricators but also from designers, beginning immediately after its development, and has already been adopted in a large number of projects. Orders received and produced now exceed approximately 4000 tons.

5.2 Mass production type high tensile strength steel for construction, HIBUIL385

High strength steel products are required for use in high-rise building construction in urban areas. On the other hand, the damage caused by the failure of beam end welds in the major earthquake which struck Kobe (Southern Hyogo Pref. Earthquake) in 1995 heightened the need for high performance steel products with a low yield ratio (yield point/tensile strength) and high toughness, combined with good weldability, in steel building frames. Recent years have also seen strong demand for reductions in construction costs, reflecting economic conditions.

NKK responded to these needs by developing a new plate, HIBUIL385, with a yield point lower limit value of 385N/mm^2, as a high tensile strength steel product which combines economy, earthquake resistance, and weldability. This product was approved by Japan's Minister of Land, Infrastructure and Transport under Article 37 of the Building Standards Act in April 2002. It was possible to produce this steel for the first time in the world by applying NKK's advanced TMCP technology, including the leading-edge accelerated cooling equipment on which this company prides itself.

The available size range of HIBUIL385 includes thicknesses from 19mm to 100mm. Important mechanical properties are a yield point lower limit value of 385N/mm^2 (range, 120N/mm^2), tensile strength lower limit value of 550N/mm^2 (range, 120N/mm^2), yield ratio of 80% or less, and 0℃ Charpy absorbed energy value of 70J or more. The chemical composition realizes a low carbon equivalent, and the specification values in the product standard are the same as those of HIBUIL355.

Currently-used steel building materials are ranked by yield point strength as 235N/mm^2, 325N/mm^2, 355N/mm^2, and 440N/mm^2. Generally, high strength steel products are used when it is necessary to lessen the weight of steel products, which can be achieved by reducing the required cross-section of members, and/or to alleviate the burden of steel frame fabrication, transportation, and erection. Considering these requirements, the strength level of steel products depends on the height of the structure, with higher strength steels being adopted in taller structures. SA440 is a high strength material which offers excellent performance, but on the other hand, it had various drawbacks because the addition of alloying elements and a complicated heat treatment process after rolling were indispensable. Among other problems, higher steel material costs were unavoidable, and strict control of the welding work was necessary when the steel frame was fabricated. For this reason, the 325N/mm^2 class had become the standard steel material for construction of high-rise buildings.

NKK is a pioneer in the field of TMCP and possesses top level manufacturing and quality control technologies, as well as a wealth of actual experience. In the present products, precise control of rolling conditions and accelerated cooling conditions made it possible to increase strength while minimizing increases in the chemical composition, thus realizing a low cost, high strength steel product, as shown in **Fig.4**. Because the weldability of HIBUIL385 is equal to that of HIBUIL325 and 355, it is possible to hold the welding costs associated with steel frame fabrication to a relatively low level, considering the high strength of the material. In comparison with a design which uses 325N/mm^2 class steel, the required steel weight can be reduced by a maximum of 15%, while the cost of the steel frame can be reduced by as much as 10%. Because the composition system also gives adequate consideration to weld impact properties, it is possible to satisfy strict performance requirements for high heat input welding when fabricating steel frames.

Among steel products with yield points in the 235～440N/mm^2 class, HIBUIL385 is the most outstanding high performance, high tensile strength steel in terms of total performance, including strength, economy, earthquake resistance, and weldability. Because HIBUIL385 offers an expanded degree of freedom in design, as well as these other advantages, it is expected to establish the 385N/mm^2 class as a new strength standard for the yield point grade of steel products for high-rise construction. Thus, by supplying this new material, it will be possible to meet diversifying social needs.

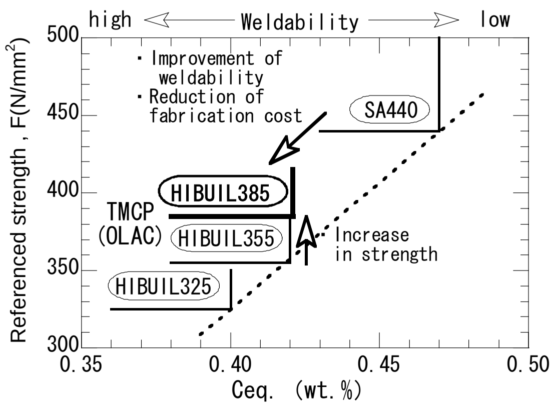

Fig.4 Concept of the developed HIBUIL385

6. Steels for construction and industrial machinery

6.1 New high tensile strength steels for construction and industrial machinery use

These high tensile strength steels are unique products which were developed independently by NKK to reduce the weight of construction and industrial machinery and are used in parts of various types. In particular, 780N/mm^2 class steel, which is used in the booms and outriggers (legs extended to two sides when a crane vehicle is fixed) of rough terrain cranes (large-scale crane trucks), must possess both high tensile strength and excellent low temperature toughness. The new high tensile strength steels (NK-HITEN LE series) developed here secure exceptional low temperature toughness in the low temperature region of -40℃, even at a high strength level of the 780N/mm^2 class, not by adding large quantities of expensive alloying elements such as Ni, but by applying micro-alloying technology and special heat treatment technology.

6.2 New wear-resistant steels

Wear-resistant steels are used in parts such as the shovels of excavators and vessels of dump trucks, and therefore must possess properties such as wear resistance, bending workability, and impact resistance. Moreover, in these products, greater importance is attached to economy than in other high tensile strength steels. Although -40℃ is an extremely low temperature for a wear-resistant steel, satisfactory toughness is secured in the new wear-resistant steel developed here, NK-Everhard 360LE, even at this temperature. This excellent low temperature toughness is obtained simultaneously with high hardness and high ductility, while minimizing the addition of alloying elements, by applying micro-alloying technology and special heat treatment technology.

Because a carbon equivalent (Lloyd's equation) of 0.40% or less is guaranteed with both of the newly developed steels mentioned above, their weldability is excellent in comparison with that of conventional steels, making it possible to reduce the preheating temperature by 25～50℃.

7. High performance 610Nmm^2 class high tensile strength steels for pressure vessel use

A variety of steel plates are used in the energy sector in applications which include energy storage facilities, chemical plants, and electric power plants. In recent years, simultaneously with the adoption of larger-scale equipment and severe operating and service conditions, increasingly strict performance requirements have been applied to these types of equipment as a result of efforts to achieve higher efficiency in installation work and thereby reduce construction costs. Where materials are concerned, recent requirements encompass higher strength, improved reliability, including weld reliability (for example, weld toughness), improved weldability, and other properties. To meet these needs, NKK developed the high performance 610N/mm^2 class high tensile strength steels shown in **Table 2**, making full use of the most advanced material property design and manufacturing technologies. NK-HITEN610U2 is equivalent to steel plate for pressure vessels SPV490 in JIS G 3115, but in comparison with the conventional steel, the new product enables reductions in both the preheating temperature and weld hardness. For the side-wall plates of large petroleum storage tanks and similar facilities, which are constructed using high efficiency high heat input electro gas arc welding, the company developed a 610N/mm^2 class high tensile strength steel for high heat input welding, NK-HITEN610E2, which gives improved joint strength and weld toughness under high heat input conditions and already has an extensive record of use. The company has also completed the development of a 610N/mm^2 class high tensile strength steel plate for low temperature service, NK-HITEN610U2L, which provides high strength in combination with low temperature toughness at temperatures down to approximately -50℃.

All the newly developed steels mentioned above were realized by applying a fully integrated combination of material property design, including micro-alloying elements, and advanced process technologies for plate manufacture. Moreover, all these products are expected to be capable of meeting the diverse new needs of the future.

Table 2 NKK's 610N/mm^2 class high performance steel plate series for pressure vessel use

Grade	Available thickness (mm)	Feature	Typical applications
NK-HITEN610U2	6≦t≦75	Excellent weldability, Superior toughness, etc.	Penstock, tank, pressure vessel, etc.
NK-HITEN610E2	6≦t≦75	Excellent weldability, Superior properties of weldments for high-heat input welding, superior toughness, etc.	Oil storage tank, etc.
NK-HITEN610U2L	6≦t≦75	Excellent weldability, Superior toughness at lower temperature, etc.	Tank for low temperature use, etc.

Readers should note that detailed descriptions of the newly developed 610N/mm^2 class high tensile strength steel plates have been omitted here due to space limitations, but may be found in item[4] of References.

8. Conclusion

This paper has described a next-generation accelerated cooling device, *Super*-OLAC, which was developed by NKK Corporation. This technology makes it possible to manufacture steel plates which satisfy a diverse range of recent property requirements, including welding and other construction-related requirements, while also offering outstanding cost performance. Features of NKK's high quality, high performance steel plates for respective fields have also been discussed by application, with emphasis on unique products which are manufactured using the new *Super*-OLAC technology.

It is possible that the 21st century will see demand for new types of steel plates which are not simply further extensions along existing lines of technology. Completely new design concepts and advanced manufacturing technologies will be necessary to meet these requirements. Although NKK Corporation will become part of the newly established JFE Steel Corporation in April 2003, the new company will inherit NKK's pioneering spirit in new process and product development, and will remain committed to development which meets new social and environmental needs.

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