NKK's State-of-the-art Flat-rolled Products Developed in the Last Decade

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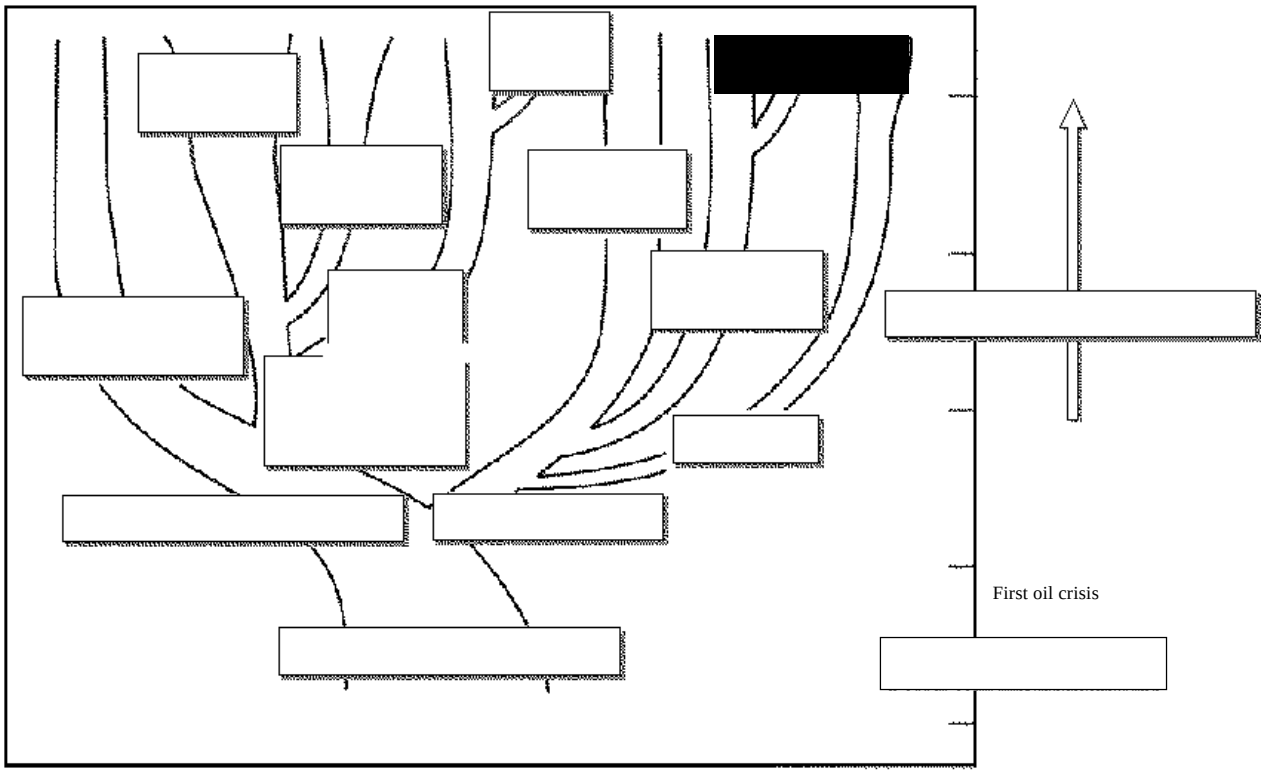
NKK has developed a wide variety of state-of-the-art flat-rolled products in response to demands from both domestic and overseas customers. This paper introduces typical new products for use in automobiles, electric appliances, can making, and enameling that were developed by NKK in the last decade based on its continuous annealing technology.

1. Introduction

A quarter of a century has passed since NKK started its first-in-the-world CAL (Continuous Annealing Line) for sheet-gauge production. During the subsequent period, the Japanese automobile companies showed remarkable growth and advancement, and also established overseas production plants. NKK responded to the needs of the Japanese automobile companies by providing an increasing amount of sheet steel and also by upgrading the quality. Since the 1990's, in particular, there has been an increasing social requirement for automobiles to be designed based on global views of energy saving, environmental protection, and resource recycling, in line with the North American CAFE (Corporate Average Fuel Economy) regulation. The demand for structural members designed for passenger protection in case of collisions and other accidents has also been strong. NKK has endeavored to develop technologies for automotive materials based on the concept of "simultaneous engineering," where all the activities for structural design, materials engineering, and production engineering are harmoniously carried out in parallel. As a result, NKK has successfully developed unique products for (1) body panels, (2) chassis and undercarriage parts, (3) safety parts and reinforcements, and (4) transmission parts. In addition, NKK developed unique technologies for automobile production. These include technologies for accurately forming high-strength steel sheets; for evaluating difficulties in forming steel sheets by CAE and selecting the most appropriate type of steel sheet for a particular application; for joining formed parts; and for evaluating the crashworthiness of automotive parts.

Since the latter half of the 1980's, NKK has also endeavored to develop new business fields for sheet steel by giving them new functionality. NKK successfully commercialized advanced steel sheet products such as non-oriented electrical steel sheets and high-Ni Invar alloy


First oil crisis

roles in the application of high-tensile-strength steels to automobiles since the 1990's.

3. Development and application of high-strength steel sheets for automobiles

Automobile manufacturing has the largest share in the use of steel sheets. NKK has developed various high-strength steel sheets to help reducing the car weight, which is the essential factor for reducing fuel consumption and exhaust gas emissions. Major achievements in the technological development of high-strength hot-rolled and cold-rolled steel sheets and their application technologies are presented below.

3.1 High-strength hot-rolled sheets for automobiles

HSLA (High-Strength Low-Alloy) steel sheet strengthend using precipitation hardening was the main high-strength hot-rolled sheet for automobiles until the 1970's. However, this material could only be used for automobile parts with limited configurations because of its poor press formability. Utilizing transformation hardening, NKK developed 590 - 780 MPa grade as-rolled-type DP steel sheets (NKHA590L, 780L) in the period of 1981 to 1984[2]. These steel sheets have a dual-phase microstructure of ferrite and martensite that is produced by controlling the cooling rate of material on the run-out table at exit side of hot strip mill. There are a number of ways to produce DP steel sheets, and NKK's products are characterized by their unique production process. Steel with about 1.0% silicon is subjected to a two-step cooling process (rapid cooling - slow cooling - rapid cooling) on the run-out table after hot rolling and then coiled at low temperatures of lower than 200 . This method stabilizes the formation of microstructure. These DP steel sheets exhibit low yield ratios, excellent work hardenability and good elongation, which make them highly suitable for parts such as wheel disks.

In the 1990's, NKK intensively researched stretch-flangeability. A series of bainite-based steel sheets (NKHA440-780SF) that have excellent elongation and hole-expansion ratio were commercialized in 1994[3]. Until those days, single-phase bainitic steel had had the best hole-expansion ratio. NKK found that it was possible to

of C, Ti and Mo to form nano-sized $TiMoC_2$ precipitates. Thus, an ultimate level of precipitation hardening was achieved. Since NANO HITEN does not contain low-temperature transformation phases, its balance between elongation and hole-expansion ratio is superior to that of the highly formable SF series sheets. Because the precipitates have particularly high thermal stability, NANO HITEN exhibits very little variance in mechanical properties compared to the conventional hot-rolled steel sheets, as shown in **Fig.2**. The low rolling load is another advantage to produce NANO HITEN, which facilitates the manufacture of thinner and wider sheets. In addition, NANO HITEN contains only a small amount of silicon, which makes it suitable for applications as a hot-rolled substrate sheet for hot-dip galvanizing.

Fig.3 shows the progress in formability of 780 MPa grade hot-rolled high strength steel sheets. In this figure,

3.3 High-carbon steel sheet

High-carbon steel sheets have been extensively used for the transmission parts and other mechanical components in automobiles. Technologies have been developed to manufacture automobile parts such as link gears and drive plates by press-forming of high-carbon cold-rolled steel sheets followed by heat treatment, instead of the conventional casting and forging methods, to reduce the part manufacturing cost. However, the manufacture of gear parts to very high dimensional accuracy requires a method to rectify incorrect shapes caused by anisotropy of steel sheets. Since the latter half of the 1990's, NKK has developed non-oriented high-carbon cold-rolled steel sheets with very little planar anisotropy but superb formability and hardenability. These products respond to the need to use high-carbon steel sheets to manufacture difficult-to-form and high-precision parts[13]. NKK successfully developed a new highly formable high-carbon steel sheet by introducing a fine dispersion of cementite and controlling the recrystallization texture. This high-carbon steel sheet can be formed by deep drawing into axially symmetrical parts with minimum earing deformation and excellent circularity, as shown in **Fig.6**.

Together with CAE-based sheet-forming and crash-worthiness evaluation technologies, these testing and evaluation technologies were used to develop TWB (Tailor Weld Blank) technology, which was viewed as promising for making parts lighter. NKK embarked on the TWB manufacturing business in 2001, targeting the domestic market.

4. Development of electrical steel sheets to support environmental protection

In 1988, NKK established a system for manufacturing and marketing non-oriented electrical steel sheets that meet the highest JIS quality specification. Since then, social awareness for the environment has been increasing, as exemplified by obligatory recycling of home appliances enforced by the Home Appliances Recycling Law; mandated energy saving for these appliances, as specified in the revision of the Law concerning the Rational Use of Energy; and the development of environmentally friendly hybrid and electric vehicles. NKK developed energy efficient electrical steel sheets against this background. Further, in response to the trend of electric machines toward using higher frequencies, NKK was the first in the world to commercialize 6.5%Si electrical steel sheets.

4.1 Non-oriented electrical steel sheet

In 1988, NKK commissioned a horizontal continuous annealing line (NKK-EFL) in the Fukuyama Works for exclusively manufacturing electrical steel sheets. Since then, the facility has been used to produce a series of e

4.2 High-Si electrical steel sheet

NKK has promoted research and development into mass production technology for 6.5%Si electrical steel sheet, which has minimal high-frequency core-losses and zero

5.1 Aluminum-killed steel sheet for shadow mask

A CRT shadow mask is produced through a series of processes consisting of photo-etching, annealing, press-forming and blackening treatment. For this reason, the steel sheet for producing shadow masks must have extremely high purity and uniformity of mechanical properties. In the early period of producing color TVs, rimmed steel was used for shadow masks. In order to eliminate defects caused by press-forming due to non-uniform elongation, NKK developed a new aluminum-killed steel sheet (NKTV-X) that is structurally uniform and has low yield-point elongation. NKTV-X gained a high reputation because of its excellent properties when used as a press-forming material for shadow masks. Since the 1990's, NKK has continued further research and development for reducing the required coercive force and for applying continuous annealing to the production of this type of steel sheet.

5.2 Invar alloy sheet for shadow mask

A basic property required of Invar alloy sheets used for producing shadow masks is low thermal expansion. In addition, these sheets need to have various material properties corresponding to the shadow mask production processes. NKK established a high-yield and high-quality integrated production system that covers all of the processes from melting the Invar alloy to production of etching substrate coils. This production system employs a high purity refining technology based on an electric furnace and secondary refining process, a hot strip mill equipped with a high-precision-shape-controlling function, and a large width, high-precision cold-rolling mill (12-rolles reversing mill). **Fig.13** is an enlarged photo of an Invar shadow mask.

Comprehensive design technologies such as computer simulation of their structures and positions in a TV tube must be used to make these newly developed products fully exhibit their magnetic shielding property. All of these technologies were fully applied to the product design.

Can-making steel sheets are under fierce competition with other materials such as aluminum and PET. NKK continues its best endeavors for research and development for creating new steels and their applications.

6.2 Enameling steel sheet

Enameling sheets must have formability that is equivalent to other cold-rolled sheets along with good enamelability. Enamelability is evaluated by factors such as enamel adherence and resistance to fish scales, bubbles, black spots, and other surface defects. When the enamel coating is applied by direct firing, the enameling steel sheets must have particularly good enamelability so as not to occur detects, because the cover coating is applied directly onto the sheet without ground coating that provides adherence-promoting agents.

Conventionally, enameling steel sheets for direct firing were manufactured by decarburized annealing of rimmed steel sheets made by ingot casting. In contrast, NKK employed continuous casting, which can more efficiently produce steels that have uniform mechanical properties, and developed an ultra-low-carbon, high-oxygen enameling steel sheet containing about 600 ppm oxygen. The new enameling steel sheets have good enamelability equivalent to the rimmed steel sheets. Today, in NKK all enameling substrates for direct firing are high oxygen steel sheets made by continuous casting. NKK also developed enameling steel sheets for two coat-two firing processing, such as titanium-bearing steel sheets that have excellent deep drawability, and boron-bearing steel sheets that are well suited for light forming, both made by continuous casting. Recently, NKK successfully employed the CAL process for producing chromium-bearing, high-oxygen enameling steel sheets that have excellent formability and enamelability. The CAL process is advantageous in cutting the lead-time for delivering the final products to customers by eliminating otherwise necessary processes and for securing uniform quality. **Table 3** lists NKK's enameling sheet products.

Table 3 NKK's enameling steel sheet products

The excellent formability of chromium-bearing, high-oxygen enameling steel sheets was developed by the application of oxide metallurgy for optimizing the morphology of oxide inclusions[28]. **Fig.17** compares the oxide morphology of the newly developed steel sheet to that of a conventional high-oxygen enameling steel sheet. The latter contains several μm MnO inclusions in diameter and very fine (Cr, Mn)-O inclusions that have a diameter of several tens nm. These fine oxide inclusions inhibit grain growth. NKK intended to mitigate this effect by making the size of oxide inclusions larger. Chromium was added to the steel to form chromium oxide precipi-

oped with a good balance of basic and application technologies. The basic technology relies on the creativity of people engaging in the development, while application