KAWASAKI STEEL TECHNICAL REPORT
No.41 (October 1999)
Advances in Iron and Steel Technologies,
Commemorating the 30th Anniversary of
Technical Research Laboratories

Recent Activities in Research of Steel Plate Products

Keniti Amano, Fumimaru Kawabata, Takahiro Kubo

Synopsis :
Major Research subjects regarding steel plates in this decade have been picked up along with the market needs. Included are the metallurgy of strengthening and toughening, advancement of TMCP and micro alloying, HAZ toughness control, welding metallurgy, corrosion science, alloying metallurgy, fatigue and fracture control, and computer metallurgy. These researches have enabled the development of many useful steel plates, such as 50 mm thick 9% Ni steel plates, high CTOD steels for offshore structures, cold cracking free HT980 steel plates for penstock, TMCP type pipe and pressure vessel steel plates for sour service, anti-corrosion steel plates for ballast tank of ships, 13Cr-5Ni martensitic stainless steel plates, 2 300 MPa maraging steel and so on. One of the highlights is the extremely low carbon bainitic steel plate, which is an as-rolled type thick 570 MPa plate being weldable without pre-heating.

The body can be viewed from the next page.

Recent Activities in Research of Steel Plate Products*


Keniti Amano
Dr. Eng., General Manager, Plate, Shape & Joining Lab., Technical Res. Labs.


Fumimaru Kawabata
Dr. Eng., Senior Researcher, Plate, Shape & Joining Lab., Technical Res. Labs.


Takahiro Kubo
Senior Researcher, Plate, Shape & Joining Lab., Technical Res. Labs.

Synopsis:

Major Research subjects regarding steel plates in this decade have been picked up along with the market needs. Included are the metallurgy of strengthening and toughening, advancement of TMCP and micro alloying, HAZ toughness control, welding metallurgy, corrosion science, alloying metallurgy, fatigue and fracture control, and computer metallurgy. These researches have enabled the development of many useful steel plates, such as 50 mm thick 9% Ni steel plates, high CTOD steels for offshore structures, cold cracking free HT980 steel plates for penstock, TMCP type pipe and pressure vessel steel plates for sour service, anti-corrosion steel plates for ballast tank of ships, 13Cr-5Ni martensitic stainless steel plates, 2 300 MPa maraging steel and so on. One of the highlights is the extremely low carbon bainitic steel plate, which is an as-rolled type thick 570 MPa plate being weldable without pre-heating.

1 Introduction

Recently, design technology of welded structures made of plate products has come to be integrated due to more stringent and diversified demands such as safety, environmental concerns, and cost savings. This paper overviews recent research on steel plate products by focusing on the metallurgical concepts behind the developments as well as characteristics, and then describes some of the principle developments in this decade.

2 Overview

The following is the primary research objectives in this decade: (1) strengthening and toughening technology, (2) performance upgrade and process saving by combining TMCP (thermo-mechanical control process) with sophisticated micro-alloying technology, (3) HAZ (heat-affected zone) toughness control, (4) optimized combination of high strength steel and welding cosumables for eliminating preheating treatment, (5) anticorrosive performance in the "sweet and sour" environments, and (6) alloyed steels. These objectives originated from commercial needs were directly linked to the new products. In addition, fundamental studies looked at (7) the evaluation of fracture, fatigue and creep performance and (8) the computational metallurgy. The market demands and the corresponding research themes are summarized in **Fig. 1** with chronological look at the development new products. The principle items are overviewed below.

Studies on strengthening and toughening led to the HT590 steel[1] of low YR (yield to tensile ratio), TS (ultimate tensile strength) 590 MPa class Cr-Mo steel for high temperature and high pressure use for chemical plant, as-rolled HT780 steel[2] for the construction machines, the heavy-gauged HT610 steel[3] for the PFBC (pressurized fluidized bed combustion) boiler vessels in medium temperature use, and the 9% Ni steel[4] of 50 mm in thickness for LNG (liquefied natural gas) storage tanks of huge capacity. The best combination of TMCP and micro-alloying technology generated the epoch-making heavy gauge HT570 steel[5] of extremely low carbon content, which is based on the new concept of utilizing ultra-low carbon bainite and eliminates heat treatments and preheating. The API5L-X80 to X100 steels[6,7] for linepipes have also been materialized.

The research on HAZ toughness has led to the development of high CTOD (crack tip opening displacement) steels[8], the 5% Ni TMCP steel[9] for LEG (liquefied ethylene gas) storage tanks, and the Mn-Mo(-Ni) steel[10] with good electron beam weldability for nuclear plants. The best-matching technology of the welding consumables to the plate has produced the HT570 steel for

* Originally published in *Kawasaki Steel Giho*, **31**(1999)1, 46–51

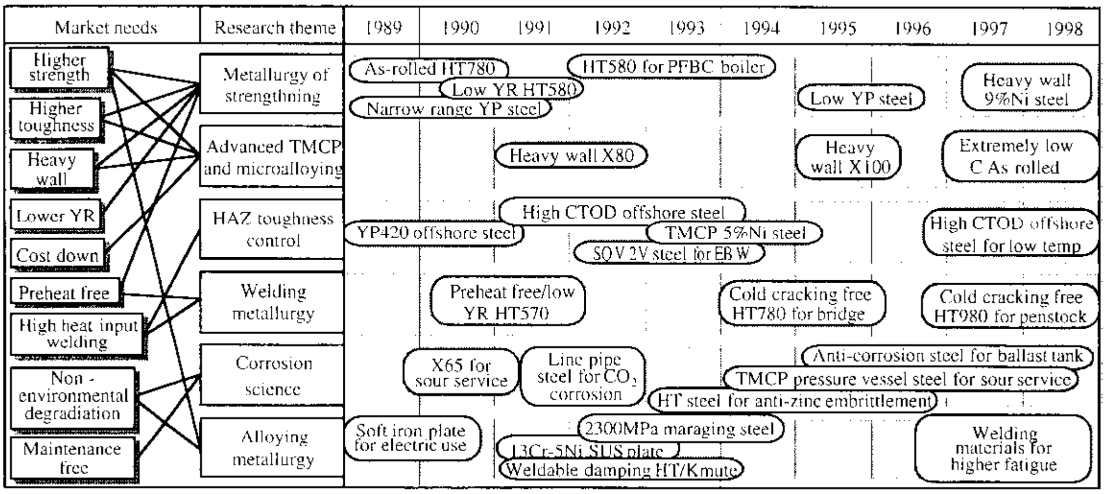

Fig. 1 Market needs, research issues and developed plate products for the last ten years

buildings, the HT780 steel[11] for bridges, and the HT980 steel[12] for penstock use. All these steels have the common advantage of saving preheating costs.

The studies on anticorrosive steels raised the X65 steels[13] for offshore pipelines in sour service and the HIC (hydrogen induced cracking)-resistant pressure vessel steels[14] as well as the anti-CO_2 corrosive steel[15] of X65 grade. Also developed were the molten zinc crack resistant steel[16] for the Zn-plated steel towers and a new steel with sea water corrosion resistance[17] for freeing double hull vessels from ballast tank maintenance.

The newly developed alloyed steels were as follows: The weldable 13%Cr–5%Ni martensitic stainless steel[18] with strong sea water corrosion resistance for ultra-high-speed hydrofoils; the HT2300 maraging steel[19], which has the highest strength among weldable steels for the motor case of space rockets; weldable anti-vibration (silent) steel[20]; and new welding consumables and procedures[21] for raising the fatigue strength of high strenght steel by converting the tensional residual stress into compression.

3 Research on Strengthening and Toughening

3.1 Advancement of TMCP Technology

The conventional TMCP was improved in cooling capability and finish-cooling, which is called "advanced MACS" ("multi-purpose accelerated cooling system"). The X80 and X100 plates were produced by introducing finely dispersed martensite owing to intensified rolling at low temperature, followed by high speed cooling at a low finish-cooling temperature.

3.2 Control of HAZ Toughness

Since 1988, the CTOD parameter with fracture mechanical basis has been used to evaluate the HAZ toughness. This parameter highlights the LBZ (local brittle zone) in HAZ as the biggest concern.

A study on the improvement of single layer HAZ toughness was concerned with the control of the HAZ microstructure for large heat input welding in which the pinning effects of TiN precipitates are normally used. Already, REM (O, S) precipitates have been introduced to sufficiently suppress the coarsening of fusion line microstructures subjected to such high temperatures as 1 400°C owing to their stability beyond 1 350°C.

On the other hand, the multi-layered HAZ shows a variety of microstructures and forms the LBZs associated with the multiple thermal cycle in welding. The LBZs were found in the following HAZs, which commonly inherit the CGHAZ (coarse grain HAZ) of low toughness as the primary microstructure created by a primary layer; the ICCGHAZ (inter-critically reheated coarse grain HAZ) which is reversely transformed partialy and the SCCGHAZ (sub-critically reheated coarse grain HAZ) which is not revesely transformed but subjected to precipitation. The former LBZ was revealed to be recovered by the tempering effect, which decomposes the detrimental martensite-austenite (M-A) constituents and is enhanced by lowering the silicon content. The latter LBZ was eliminated by minimizing the precipitating elements such as Nb and V.

The contemporary TMCP technology has led to great achievements in this field. The above mentioned technologies are used for almost all shipbuilding steels of the TS 490 MPa class as well as the current commercial high strenght offshore structural steels of the YP (yield point) 420, 500, and 550 MPa classes. A high grade steel[8] of YP 420 MPa class with a large CTOD of more than 0.3 mm at −40°C was commercialized in 1998.

3.3 Improvement of Anti-sour Performance

In 1988, the world's first offshore pipeline using ex-

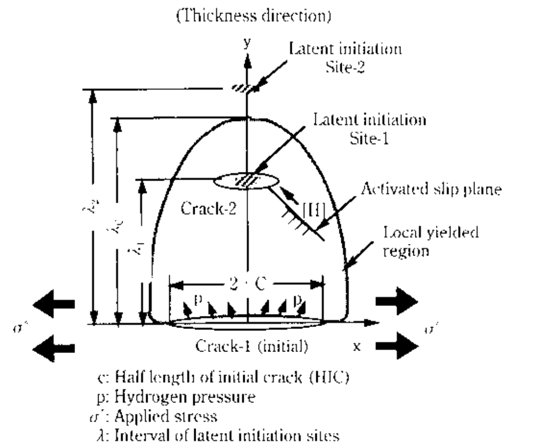

Fig. 2 Schematic explanation of the "latent initiation site model"

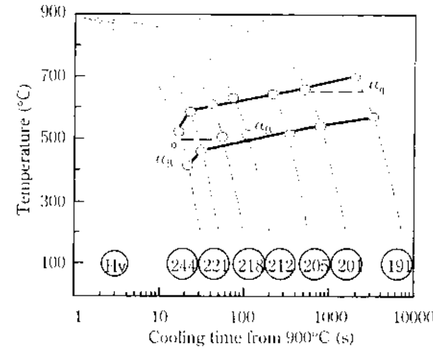

Fig. 3 CCT diagram of extremely-low carbon bainitic steel

clusively TMCP steels was installed. Since then, the linepipe steels of TMCP type have become irreplaceable and has been improved their performance. The improvement in resistance to wet H_2S environments (anti-sour resistance) such as HIC and SSC (sulfide stress corrosion cracking) was especially remarkable. The grade of steels in this application was also shifted from X60 to X65 in this period. It is now reaching X70 and even X80 with some limitations. These advancements have resulted from the past 10 years of research.

The biggest research concerns were with the enhancement of HIC-resistance and the achievenment of SOHIC (stress oriented HIC)-resistance. The SOHIC is an alternate type of SSC for relatively low strength linepipe steels.

A study on the severer acid "NACE solution environment" established the advanced fundamental design in which the hardness of the center segregation is decreased by lowering carbon content and relaxing the limitation of Mn addition for more flexible control of properties.

A study on HIC led to the technology for SOHIC resistance. The characteristic behavior of the SOHIC, which propagates perpendicularly to the applied stress direction, was closely and theoretically investigated. The latent initiation site model (**Fig. 2**) from the study was introduced to explain the propagation mechanism and propose the most suitable microstructural control.

An example of microstructural controls is dispersing the second phase by TMCP. The research successes have been incorporated into ASTM A516-70 and A841 steels for pressure vessels in chemical plants.

4 Extremely-low C Bainitic Steel

Strengthening generally makes it more difficult to maintain weldability. Kawasaki Steel has overcome this dilemma by developing a new type of steel based on the concept of maintaining a constant microstructure. Methodological points in the concept are lowering carbon content below its solubility limit in the ferrite phase (about 0.02 mass%) and keeping the bainitic single phase microstructure for high strength (**Fig. 3**). This concept has made it possible to obtain consistent strength as high as 590 MPa class for a thickness range from 10 to 100 mm even in as-rolled condition. The extremely-low carbon has also completely eliminated the need for preheating. In addition, the heat-affected zone of the new steel has been revealed to be less dependent than even on welding heat input. The newly developed extremely-low C bainitic steel has the following features:

(1) The minimized dependence of microstructure on cooling rate facilitates strengthening in as-rolled condition.
(2) The difficulty of martensite to form in high rate cooling suppresses hardening and facilitates welding.
(3) The difficulty of an M-A constituent to form even in particular cooling, enables such large heat input welding as up to 20 kJ/mm.

A typical chemical composition of extremely-low C bainitic products of 570 MPa class with thickness up to 75 mm is like 0.012%C-0.3%Si-1.56%Mn with microalloying elements such as Cu, Ni, Nb, and B. Values of both Ceq and Pcm, 0.294 and 0.137 respectively, are much smaller than in the conventional 570 MPa plate products.

5 Ultimate Strengthening

In this decade, strengthening technology has also made great advancements. For example, the strenght of 2 300 MPa has been achieved by the precipitation hardening mechanism of metallic compounds[19]. Studies have looked at the expansion of the non-recrystallization region by boron, refining of microstructure by the reverse shear transformation, and toughening by heat treatment with control of precipitation behavior of metallic compounds. The successes of these studies led

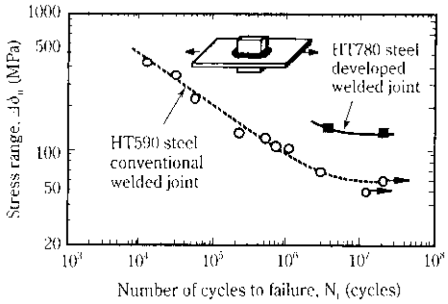

Fig. 4 S-N curves of non-load-carrying fillet welded joints

to the optimum chemistry and manufacturing process and commercialization of the new maraging steel of 2 300 MPa in strenght with such chemistry of 18%Ni-10.5%Co-5%Mo-0.6%Ti-B. This has been applied to the motor case of domestic rockets of ISAS (The Institute of Space and Astronautical Science).

6 Fatigue Strength

In spite of the progress in high strength plate products, their application to welded structures has been limited due to the fact that the fatigue strength of welds is kept as low as that of mild steel because tensional stress remains in the vicinity of the toes of welded beads. A collaborated research program[21)] with NRIM (National Research Institute for Metals) has brought forth the new consumable of 10%Cr-10Ni-Fe type. The residual stress is converted into compression and fatigue strength of the weld is improved by using the new welding consumable with low transformation temperature such as the room temperature as shown in **Fig. 4** because the expansion of weld metal overcomes thermal shrinkage. An actual application is now being planned and a high strength steel application to welded structures is expected to improve safety.

7 Conclusions

The demand for and on plate products has been diversifying and new products are expected to cut the total cost from the steel maker through the final user. Under these circumstances, new product development should emphasize users' concerns more than ever. In addition, the research objectives should be carefully selected so as to better meet the rapid changes in demand.

References

1) T. Koseki, K. Uchida, and K. Amano: The 8th Int. Cong. of Heat Treatment of Materials, ISIJ, (1992), 45
2) K. Amano, O. Tanigawa, C. Shiga, and T. Okumura: *Kawasaki Steel Giho*, **21**(1989)1, 19
3) N. Itakura, S. Deshimaru, and I. Nakagawa: *Kawasaki Steel Giho*, **30**(1998)3, 38
4) T. Kubo, A. Omori, and O. Tanigawa: *Kawasaki Steel Giho*, **30**(1998)3, 167
5) M. Okatsu, T. Hayashi, K. Amano: *Kawasaki Steel Technical Report*, (1999)40, 49
6) F. Kawabata, K. Amano, O. Tanigawa, T. Hatomura, T. Yamaura, and Y. Sujita: '92 Int. Offshore Mechanics and Arctic Engineering Sym., ASME, (1992), 597
7) F. Kawabata, M. Okatsu, K. Amano, and Y. Nakano: Proc. of the 2nd Int. Pipeline Technology Conf., Ostend (Belgium), Sept. (1995)II, 263
8) M. Hisada, T. Miyake, and F. Kawabata: *Kawasaki Steel Technical Report*, (1999)40, 49
9) Y. Morikage, F. Kawabata, and K. Amano: *CAMPS*, **8**(1995), 1352
10) M. Nishimori, K. Uchida, A. Matsuzaki, and K. Amano: *CAMPS*, **8**(1995), 1352
11) K. Ohi, N. Itakura, F. Kawabata, and K. Amano: J.W.S Forum, Preprints of the National Meeting of J.W.S, 58(1996), 11
12) N. Itakura, K. Yasuda, and M. Aoki: *Kawasaki Steel Giho*, **30**(1998)3, 174
13) F. Kawabata, K. Amano, T. Hatomura, J. Kudo, and T. Kawauchi: 9th Int. Offshore Mechanics and Arctic Engineering Sym., ASME, (1990)
14) F. Kawabata, O. Tanigawa, and I. Nakagawa: *Kawasaki Steel Technical Report*, (1999)40, 63
15) M. Murakami, O. Tanigawa, M. Kimura, T. Hatomura, and T. Yamaura: *Kawasaki Steel Giho*, **24**(1992)4, 307
16) T. Koseki and K. Amano: *Kawasaki Steel Giho*, **25**(1993)1, 20
17) K. Shiotani, R. Ikeda, Y. Yamane, F. Kawabata, and K. Amano: *CAMPS*, **11**(1998), 456
18) T. Kimura, H. Oka, H. Mishiro: *Kawasaki Steel Giho*, **30**(1998)3, 148
19) T. Kimura, A. Matsuzaki, K. Amano, O. Tanigawa, M. Nayama, and T. Nishida: *CAMPS*, **7**(1994), 1848
20) T. Koseki, K. Amano, O. Tanigawa, and H. Ishii: *CAMPS*, **6**(1993), 1839
21) A. Ohta, O. Watanabe, K. Matsuoka, C. Shiga, S. Nishijima, Y. Maeda, N. Suzuki, and T. Kubo: Preprints of the National Meeting of J.W.S, 61(1997), 520