Title	Progress in Structural Steels for Bridge and Linepipe
Author(s)	Shibayanagi, Toshiya
Citation	Transactions of JWRI. 2006, 35(1), p. 1-7
Version Type	VoR
URL	https://doi.org/10.18910/8731
rights	
Note	

Transactions of JWRI, Vol.35 (2006), No. 1

Progress in Structural Steels for Bridge and Linepipe†

KOMIZO Yu-ichi*

Abstract

This paper considers some of the developments in steels for bridge and line pipe use. These are an essential part of the social infrastructure and a national asset. Construction economy as well as safety is an important consideration. To meet the target of safe and economical construction, steel manufacturers have made improvements to their technologies.

KEY WORDS: (bridge) (line pipe) (high strength steel) (TMCP) (weldability) (weathering steel) (X100) (X120)

1. Steel Plates for Bridge Use

Asian countries lag behind the US and EU countries in road construction, even in Japan. However construction is expected to increase in the inland and onshore regions, which will increase the ratio of structures such as bridges compared with earthworks. **Figure 1** shows the bridge extension length in Japan. Bridges are an essential part of the social infrastructure and a national asset. Therefore, bridge construction economy and reduction of life cycle cost (LCC) are important considerations. With rising demand for large-scale structures and higher efficiency in fabrication, high strength steel plate with high performance which offers high strength and high toughness combined with excellent weldability and economy has been strongly required. Weathering steels have been also commercialized which greatly reduce the bridge LCC, together with new rust stabilization treatment technologies which extract the maximum performance from such steels.

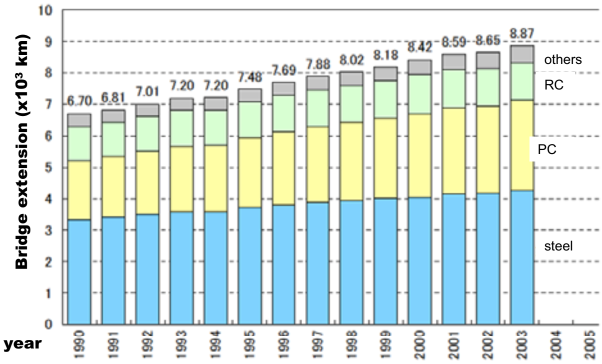
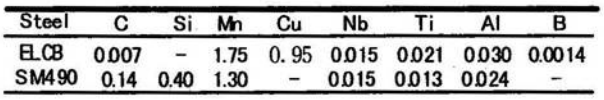


Fig.1 Bridge extension length in Japan

1.1 High Strength Steel Plates for Bridge Use

Table 1 Chemical compositions of the ELCB and SM490 steels (mass%)



Steel	C	Si	Mn	Cu	Nb	Ti	Al	B
ELCB	0.007	–	1.75	0.95	0.015	0.021	0.030	0.0014
SM490	0.14	0.40	1.30	–	0.015	0.013	0.024	–

The Thermo-Mechanical Control Process (TMCP) is the method for control of mechanical properties of steels through invariable microstructure control integrated with precipitation hardening. Table 1 shows the chemical compositions of extremely low carbon bainitic (hereafter ELCB) steel. Lowering carbon content below 0.02mass%, which is the maximum solid-soluble limit to ferrite, and optimizing the other alloying elements such as Mn, B and Nb for lowering the transformation temperature can make the steel have a uniform extremely low carbon bainitic microstructure independent of a cooling rate (see **Fig.2**) [1]. The cooling rate dependence of hardness is shown in **Fig.3**[1]. As for the ELCB steel, the increment with the rise of cooling rate from 0.1 to 55K/s was 4 points in contrast to 89 points for conventional SM490 steel. This weak cooling rate dependence of the microstructure and the hardness for the ELCB steel indicates that large section steel products with higher strength, lower hardenability of HAZ in the welding process, can be easily produced by using the TMCP. Furthermore, the TMCP can vastly improve the strength of a steel by invariable microstructure control associated with precipitation hardening.

A typical chemical composition of the ELCB steel plates of HT570(600 MPa) class with thickness up to 75 mm is of 0.012mass%C-0.3mass%Si with micro-alloying

---

† Received on May 12, 2006
* Professor

Transactions of JWRI is published by Joining and Welding Research Institute, Osaka University, Ibaraki, Osaka 567-0047, Japan

elements. For this application, the basic TMCP is adopted so that precipitation hardening is not necessarily used. Both values of Ceq and Pcm, 0.294 and 0.137 respectively, are remarkably smaller than those of the conventional HT570 plate products.

The ELCB steel plates exhibit the excellent uniformity in microstructure and therefore in strength.

The ELCB steel was also shown to exhibit good heat-affected zone toughness for a wide range of welding heat inputs owing to its small dependency on cooling rate.

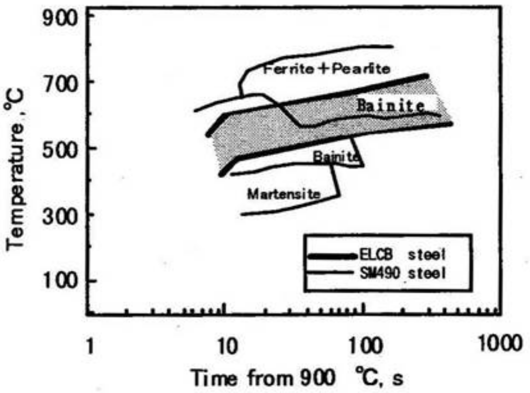


Fig.2 Comparison of the CCT diagrams between the ELCB and SM490 steels.

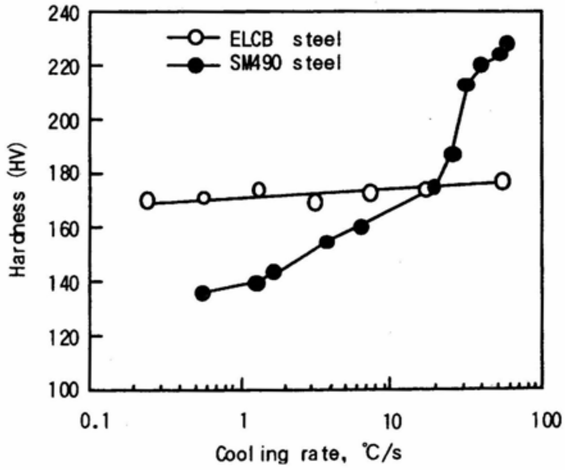


Fig.3 Relationship between the cooling rate and hardness of the ELCB steel.

Another advanced steel is Ausformed Bainite Steel utilizing a fine ausformed bainite microstructure which is characterized by the reduction control in the unrecrystallized austenite region and by the cooling control in the bainite transformation region[2]. **Figure 4**(a) shows the typical B1 type upper bainite structure having large packet size. On the other hand, Fig. 4(b) shows fine ausformed bainite structures in which coarse bainite packets are not observed. Heavy deformation is required for the remarkable refinement of bainitic ferrite laths, and deformation less than 30% is not effective on the reduction of the length significantly.

Mechanical properties of Ausformed Bainite HT570 steel developed for bridge use are shown in **Table 2**. High tensile strength and superior toughness have been obtained both in base metal and welded joints up to 100mm in thickness. High heat input electro-gas arc welding up to 20kJ/mm can be also applicable to this steel.

The extremely low Ceq and low Pcm also makes the high strength steel be free from a preheating owing to its low hardenability.

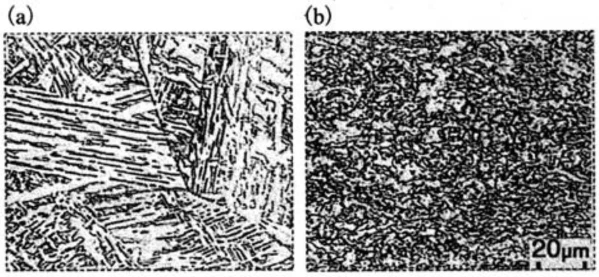


Fig.4 Microstructures of (a)conventional upper bainite and (b)ausformed bainite.

Table2 Mechanical properties of ausformed bainite steel (HT570)

	Base Metal			Welded Joint (t=45mm)			
Thickness [mm]	YS [N/mm^2]	TS [N/mm^2]	vE-5 [J]	Heat Input [kJ/mm]	Welding Process	TS [N/mm^2]	vE-5(FL) [J]
45	523	632	306	20.0*	EGW	643	115
100	508	628	317	5.0	SAW	664	217
				10.0		650	195

Tensile test specimen:D14GL50 (1/4t,C-dir.) Tensile test specimen:Full thick. 25width
Impact test specimen:2mmV (1/4t,full size,L-dir.) Impact specimen: 2mmV(1/4t,full size)
*Thickness decreased to 35mm

1.2 Weathering Steels

Researches on iron rust hitherto have been conducted in connection with weathering steels because of the advantage of their use as the structural materials that meet the concept of minimum life-cycle cost of infrastructure. In the early days, studies on weathering steels placed a focus on their corrosion behavior in atmospheres polluted with sulfurous products, SOx. Studies of the long-term atmospheric exposure tests in Japan, however, have revealed that airborne salinity has the major effect on the corrosion of steels, while in other part of East Asia the effect of Sox is still predominant[3,4]. The recent trend in weathering steel is more and more concerned with the development of resistant steels in high-salinity environments.

The conventional weathering steel, i.e. JIS SMA, can be used without painting in regions where the amount of airborne salt does not exceed 0.05 mdd ($mg/dm^2/day$), because high airborne salt makes it difficult to stabilize rust, as observed on shore and in coastal areas[5]. A new generation of Ni-added high corrosion resistant weathering steels has been commercialized, which can be used without painting even in such environments with high airborne salt[6,7].

A new technology for accelerating the formation of a stable rust layer on the weathering steel was accomplished by developing a special surface treatment[8,9]. The process was based on a survey of stable rust layer deposited on weathering steel during a quarter of a century of service in industrial areas. The special surface treatment was designed to accelerate the formation of Cr-substituted goethite and to inhibit the formation of flowing rust in the early stage of service. The rust layer formed on weathering steel has a double layer structure and protects steel from corrosion because the formation of a bipolar membrane suppresses cathodic reaction (see **Fig.5**) [9] . Thus the formation of α -FeOOH in the inner layer and γ -FeOOH in the outer layer is important in the protection ability of the rust.

Figure5 shows the relationship between corrosion rate of weathering steel and the ratio of α -FeOOH/ γ -FeOOH in the rust. Corrosion rate decreases to nearly zero when the ration of α -FeOOH/ γ -FeOOH in the rust exceeds 1.4. This ratio of α -FeOOH/ γ -FeOOH can be defined as a rust stability index, that is, when this value exceeds 2, it can be said that the rust layer is stable.

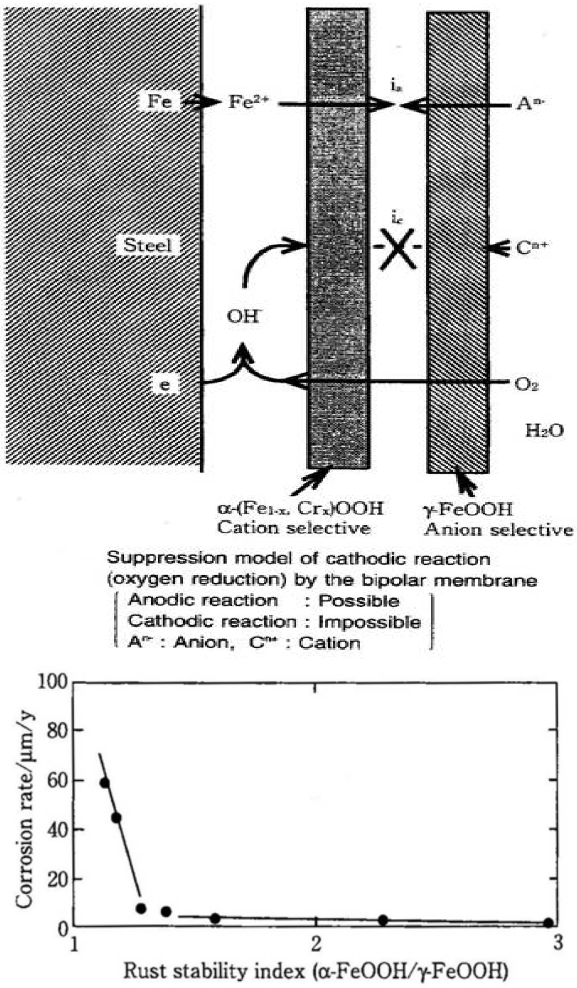


Fig.5 Suppression model of weathering steel and the effect of rust stability undex on the corrosion rate.

1.3 Other Technologies for Bridge Use

Other recently developed products include longitudinally profiled (LP) steel plates, in which the thickness continuously varies in the longitudinal direction by applying a rolling profile control technology, and the special welding consumables and technologies for improving the fatigue strength of the welded joints.

It has been shown that the low-temperature transformation welding consumable that contains large amount of Cr and Ni can bring compressive stress around weld toes (see **Fig.6**) and is expected to improve the fatigue strength of welded joints of high strength steel plates[10]. To prevent fatigue fracture is one of the most important challenges to improve the safety and reliability of steel welded structures.

Many studies of how to reduce stress concentrations around weld zones have been carried out from the viewpoint of structural design, while little has been studied from the materials viewpoint, because it is well known that the fatigue strength of welded joints converges in a limited range regardless of material strength.

A new dual phase steel which has excellent fatigue properties was developed.

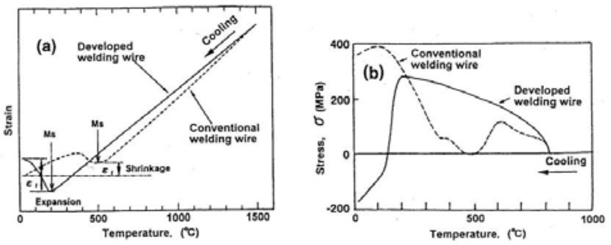


Fig.6 Variation of strain or stress in low transformation temperature weld metal. (a)free deformation condition, (b)strain constrained condition.

2. Line Pipe Steels

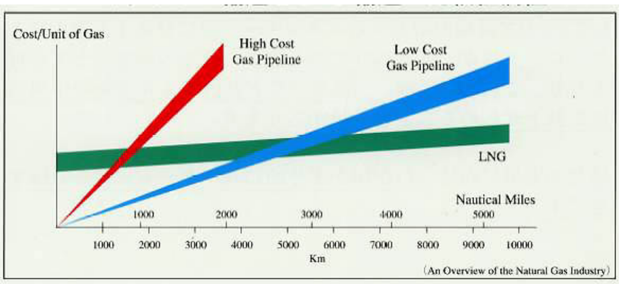


Fig.7 Cost of pipeline transportation and LNG system.

The need to replace oil and coal as the primary sources of energy has resulted in an increase in the exploration and exploitation of natural gas resources often found in remote, inaccessible environments. It is important that R&D seeks ways to get such gas to the market as cheaply as possible. These technologies include liquefied natural gas(LNG), conversion of gas to liquids, generation of high DC voltage electricity for long distance transmission and pipeline transportation of gas, with the recognition that the solution for a given application may be a combination of these and other technologies. The pipeline transportation is more economical than the LNG system in case of short transport distances, as shown in **Fig.7**.

The growing demand for natural gas supplies in North America, Europe, China, Korea and other regions of SE Asia has caused attention to be given to a number of potential pipeline projects to transport gas from remote fields to market (see **Fig.8** in case of East Asia).

The recent development of high strength steel linepipe offers gas producers the opportunity to lower the total cost of long-distance gas transmission pipelines, thereby lowering the cost of supplying gas to market by fully capturing the benefits of high-pressure transmission for large volumes of gas as shown in **Fig.9**.

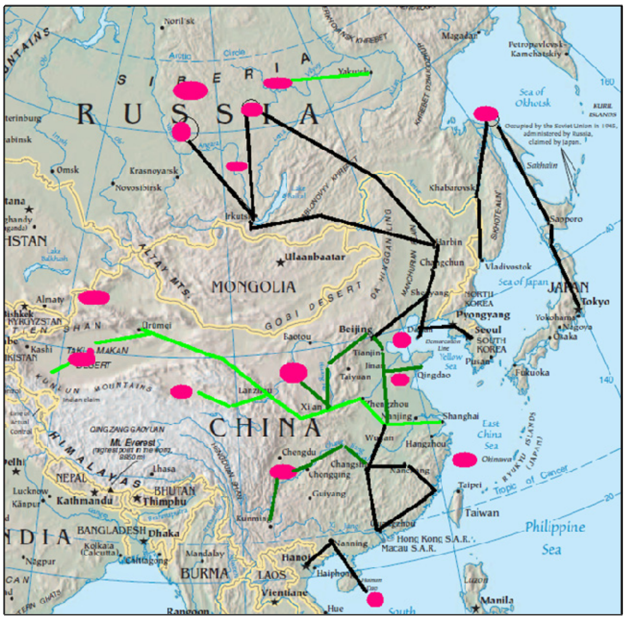


Fig.8 Pipeline projects in East Asia.

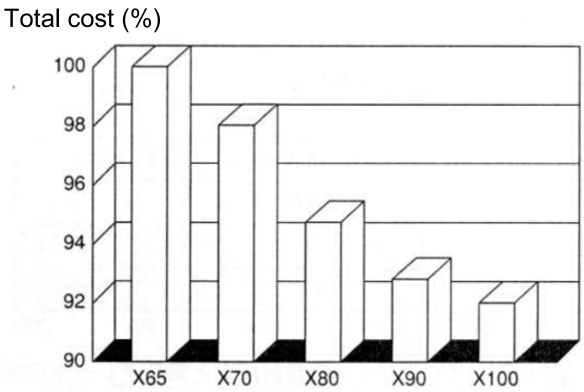
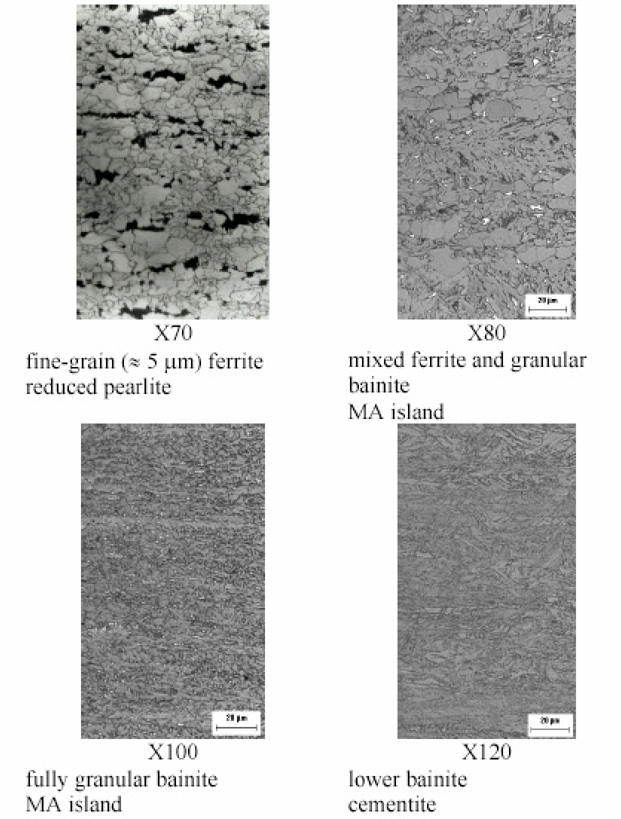


Fig.9 Lower cost installation requires the high strength steels.

To maximize economic advantages, the use of higher-strength steels (X80 and over) in linepipe systems has been investigated [11]. X80 grade steels have been developed and utilized for gas linepipes. Regarding X100, this steel has been developed and the characterization of prototype pipes has been extensively studied by pipe manufacturers [12,13] and by a joint industry project of major oil companies [14]. In the case of X120 grade steel, a cooperative research and development effort on ultra high-strength linepipe steels has been conducted on manufacturing and applying the steel to high-pressure gas linepipes [15].



X70
fine-grain (≈ 5 μm) ferrite
reduced pearlite

X80
mixed ferrite and granular bainite
MA island

X100
fully granular bainite
MA island

X120
lower bainite
cementite

Fig.10 Typical microstructures for X70 to X120 grade

The metallurgical design changed accordingly, a major issue being the optimum microstructure required to achieve the target properties forX70, X80, and later X100 and X120 grades. The overall pattern isreported in **Fig.10**[16].

Grain refinement of ferrite in ferrite-pearlite microstructure was the key point for X70 control rolled plates. For X80 plate a different approach was made possible, based on the development of microstructure containing increasing amounts of “acicular ferrite” , a carbide-free form of ferritic bainite, instead of pearlite. The adoption of on-line cooling of the plate at moderate rates (10-15°C/s) just after rolling allowed the development of acicular microstructures avoiding significant increase in alloy design to increase steel hardenability.

Acicular ferrite was invariably coupled with islands of a hard phase, which proved to be high-carbon martensite, generally containing also retained austenite.

The name MA "constituent" was introduced for such dispersed phases. The aggregate of acicular ferrite and MA constituent is sometimes called "granular bainite" – and this is adopted in the following. Since MA islands have a major effect on mechanical properties, optimisation of dispersed phases was subjected to detailed analysis.

For X100, a matrix fully consisting of granular bainite with suitable amounts of MA as dispersed phase proved to be the best solution, although a severe conditioning of austenite by a careful control of TMCP was shown to be needed in order to guarantee suitable DWTT toughness at such high strength levels.

The X120 grade, however, is out-of-reach by this approach [17]. Another type of low-carbon bainite with a lower transformation temperature range has been therefore considered, the so called "lower bainite". The increase in hardenability needed to suitably modify the CCT diagram is achieved by addition of B, which has a well-known effect on bainite hardenability when present as "solid solution" at a level of few ppm. Specific mention must be made of the strength/toughness combinations in bainitic steels.

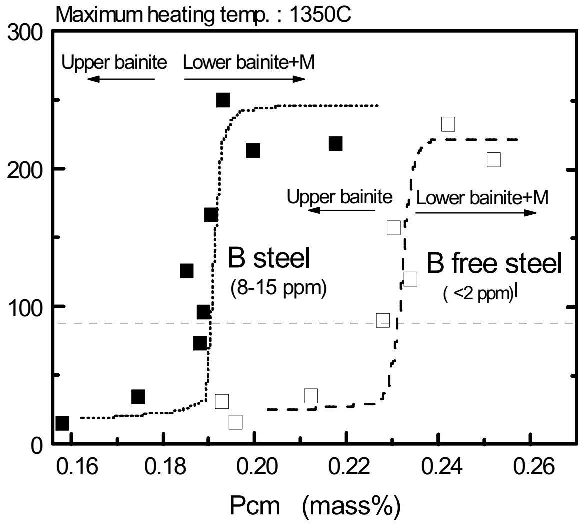


Fig.11 Effect of Pcm value on HAZ toughness

Heat affected zone (HAZ) toughness was optimized by several methods. The carbon and silicon contents were kept low to minimize the amount of MA (martensite-austenite) constituent. Microalloys (Nb, V and Ti) were carefully selected to help control MA, limit grain growth, and limit adverse precipitation effects. N, P and S contents were reduced for general cleanliness and the hardenability was controlled to ensure that during the weld thermal cycle, transformation to fine lath based structures would occur.

The effects of alloy content (the Pcm value), particularly boron level, on the low temperature toughness of synthetic HAZs are shown in Fig.11[18]. This data was generated using a weld thermal cycle simulator, relevant coarse grain HAZ thermal cycles (Peak temperature= 1350°C, Holding time= 5 s), and Charpy V-notch testing. The results indicate that a threshold Pcm value exists, above which toughness is markedly improved. Above the threshold, high toughness is associated with lower bainite and martensite, presumably due to the enhanced microstructural refinement. At Pcm values below the threshold the microstructure is dominated by degenerate upper bainite, which contains larger packets, thicker laths, and larger areas of MA.

2.2 Longitudinal Seam Weld

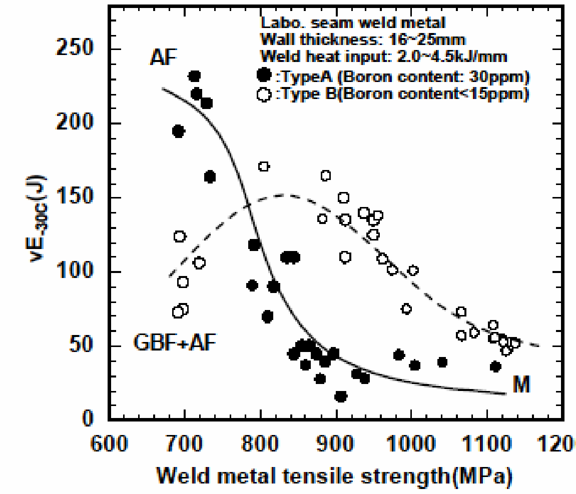


Fig.12 Relation between Charpy absorbed energy and weld metal strength.

During extensive experimental work to investigate the properties of the seam weld, it was determined that weld metal strength can be controlled primarily through hardenability. **Figure 12** shows the relationship between Charpy absorbed energy at -30°C (vE-30°C) and weld metal tensile strength. In the figure, data from two families (types) of weld metal are included. Type A was produced using a boron added flux. The boron content was around 30ppm. This type of weld metal had high absorbed energy when the tensile strength was around 700MPa because the microstructure was dominated by fine acicular ferrite. Within this family of weld metal, as the microstructure changes to bainite/martensite at strengths greater than 900MPa, the Charpy energy decreases to less than 50J.

The family of weld metals denoted type B was produced using a flux with lower boron content as compared to type A. Type B boron content was 15ppm or less. At strengths of about 700MPa, type B weld metal had lower absorbed energy than type A because grain boundary ferrite was present in the microstructure. Within the type B family, as strength increases from 700 to 800 MPa, and grain boundary ferrite is eliminated, absorbed energy increases to about 150J. As the strength of type B is further increased to above 800MPa, some of the acicular ferrite is replaced with bainite/martensite and the absorbed energy begins to decrease. At tensile strengths of about 1000MPa (the strength of interest for an X120 seam weld), type A weld metal contains a bainite/martensite microstructure whereas type B still retains a significant amount of acicular ferrite.

To further investigate the deformation capacity of the longitudinal seam weld, FEM analysis was conducted for various ratios of HAZ strength to weld metal strength. The purpose was to study the effects of HAZ softening and matching ratio on the strain concentration at the HAZ (i.e., the weld toe) during seam weld deformation. **Figure 13** shows the results of this FEM analysis. Both overmatching and the reduction of HAZ softening are necessary to reduce the strain concentration at the weld toe. The toughness of weld metal tends to decrease with increasing strength. On the other hand, higher weld metal strength is an advantage to achieve overmatching. Therefore, to obtain an optimum balance of properties, controlling (limiting) the base metal strength is important to simultaneously achieve overmatched weld joints and sufficient toughness.

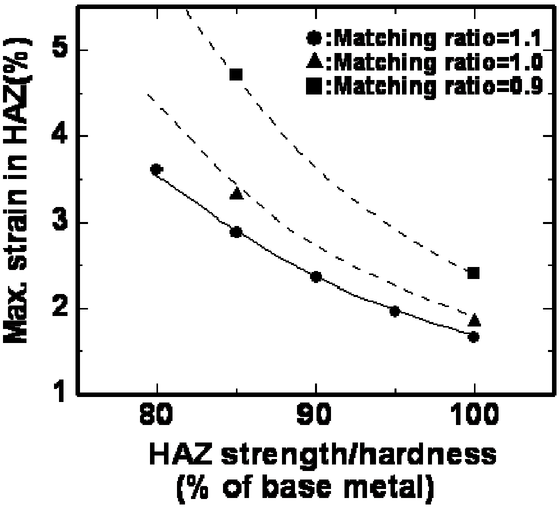


Fig.13 Estimation of strain distribution at the welded portion by FEM.

2.3 Technical Issues for The Application of High Strength Line Pipe

There are several main technical issues to be clarified before commercial application, and these are listed below[19].

(1) Evaluation of yield strength

The evaluation of the yield strength of the steel is the basic parameter required in order to know the properties of the pipe. It is reported that the Bauschinger effect of high strength line pipe cannot be ignored [20]. The yield strength of X100 from the flattened specimen is artificially decreased by the Bauschinger effect. As the yield strength of the round bar without flattening possibly represents the yield strength of the pipe.

(2) Strength of seam weld joint and field weldability

The weld joint strength is normally higher than the tensile strength of the base metal for line pipes up to X80 grade. It is pointed out that overmatching and softening are the controlling factors for weld joint strength. In X100 and X120, it is not always the case that the joint strength exceeds the base metal strength, and the fracture occurs in the base metal.

(3) Yield/tensile ratio and deformability

The yield/tensile ratio of X100 and X120 pipes may exceed 0.93 of the API requirement, and the deformability will be smaller than for ordinary grades. The necessity of modifying standards and pipe line construction codes has to be investigated in the case of any processes, which involve plastic deformation of pipes, such as field cold bending and field hydrostatic testing exceeding 100% SMYS.

References

[1] T.Hoshino, M.Okatsu, T.Kimura and K.Amano; Proc. Int.Conf.Advanced Structural Steels (ICASS 2002), p.97

[2]K.Fujiwara, S.Okaguchi, Y.Komizo, K.Arimochi, T.Kawabata and A.Nagayoshi; Proc. Int.Conf.Advanced Structural Steels (ICASS 2002), p.93

[3]Y.Tsujino, Y.Maeda, T.Mizoguchi and S.Hatakeyama; Proc.45th Japan conf. Materials and Environment, 1998, p.371

[4] T.Kodama; Proc. Ultra-steel 2000, p.243

[5] Ministry of construction's civil engineering laboratory, Japan steel materials club, and Jpn.Assoc. Bridge construction(ed.), Joint research report on application of weathering steel to bridge(XX), 1993

[6] I.Kage, K.Matsui and F.Kawabata; JFE technical report, No.5(2005), Mar., p.37

[7] Y.Sakata, Y.Fujii, et.al.; Nippon Steel technical report, No.77,78 (1998), July, p.47

[8] H.Kishikawa, H.Miyuki, K.Kashima, M.Kamiya and S.Hara; Bohsei Kanri (Corrosion Control), No.2, 2000,p.5

[9] S.Hara, K.Kashima, H.Kishikawa, H.Miyuki and T.Misawa; Tetsu to Hagane, Vol.87(2001), p.43

[10] A.Ohta, O.Watanabe, K.Matsuoka, Y.Maeda, N.Suzuki and T.Kubo; Quar. J. JWS, 19-2(2000), p.373

[11] N.Sanderson, R.K.Ohm, and M.Jacobs; Oil & Gas Journal, (1999),pp54-57

[12] T.Hashimoto, Y.Komizo, M.Tsukamoto and I.Takeuchi; The Sumitomo Search vol.37(1988), pp93 –104

[13] F.Kawabata; Proc of Symposium on "the state-of-the-art and future of pipeline", Osaka(1995), pp1-9

[14] J.Hammond, and N.A.Millwood; Proc of the 3rd Int. Pipeline Technology Conf. Brugge, Ed. by Denys, R,(2000) pp69-88

[15] D.P.Fairchild, M.L.Macia, S.D.Papka, C.W.Petersen, J.H.Stevens, S.T.Barbas, N.V.Bangaru, J.Y.Koo and M.J.Luton; Proc of pipe dreamer's conference (Application & Evaluation of High-Grade Linepipes in Hostile Environments), Yokohama,(2002), pp307-321

[16] M.Pontremoli; Proc.15th.International Offshore and Polar Engineering Conference, ISOPE, Seoul,Korea, June(2005),

p.31

[17] J.Y.Koo, D.P.Fairchild, H.Asahi, Y.Komizo, M.J.Luton,; Proc 13th International Offshore and Polar Engineering Conference; ISOPE, Honolulu, Hawaii, USA.(2003)

[18] S.Okaguchi, A.Yamamoto, I.Takeuchi, D.P.Fairchild, and J.Y.Koo; Proc 13th International Offshore and Polar Engineering Conference; ISOPE, Honolulu, Hawaii, USA.,(2003)

[19] Takeuchi, I, Fujino, J, Yamamoto, A and Okaguchi, S. (2002) “The prospect of high-grade steel pipe for gas pipelines” Proc of pipe dreamer’s conference (Application & Evaluation of High-Grade Linepipes in Hostile Environments), Yokohama, pp185-202

[20] G.Hohl, G.Knauf and G.Vogt; Pipeline Technology, Volume I, (2000), p.549