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Status & Prospects of Shipbuilding Steel and Its Weldability†

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Abstract

Being combined with TMCP steels, a variety of welding technologies have been developed to increase welding speed, deposition rate and integrity of welds. More, concerns have been extended to the safety and the durability of ships, and thereby, improved HAZ toughness, crack arrestability, corrosion resistance and fatigue strength have been demanded for structural steel plates for shipbuilding. In this paper a lot of progress were reviewed over the last thirty years in steel plates and welding technology for shipbuilding.

KEY WORDS: (shipbuilding steel) (TMCP) (HAZ toughness) (fatigue strength) (microstructure)

1. Introduction

Reducing weight and increasing energy efficiency have been prime concerns to achieve the large-size ships such as ultra large crude oil carriers (ULCC), very large crude oil carriers (VLCC), liquefied gas carriers, cargo ships, and passenger carriers , while reducing construction cost and time also has been increasingly required in shipbuilding industry. Steel plates produced by thermo-mechanical control processes (TMCP) have provided an effective solution to those requirements, offering better combinations of strength and toughness without losing weldability, as compared with conventional normalized steels[1-3]. The use of the TMCP steel plates with higher strength has made it possible not only to reduce the weight of the ship but also to apply high speed, high heat input welding to the construction, because of better weldability and HAZ toughness. Being combined with TMCP steels, a variety of welding technologies have also been developed to increase welding speed, deposition rate and integrity of welds. More recently, concerns have been extended to the safety and the durability of ships, and thereby, improved HAZ toughness, crack arrestability, corrosion resistance and fatigue strength have been demanded for structural steel plates for shipbuilding.

2. TMCP steels

In recent years, high performance high strength steel plates have been mass-produced by TMCP technologies. Because optimum adjustment of the hot-rolling and subsequent cooling conditions can be realized with these technologies, product properties are superior to those obtained with off-line heat treatment (see **Fig.1**)[4].

The TMCP steels have offered improved combinations of strength and toughness as compared with conventional steels, owing to the refined mixed microstructure of ferrite and bainite. This characteristic microstructure of TMCP steels is primarily achieved by hot-rolling in the non-recrystallized temperature region and subsequent accelerated cooling.

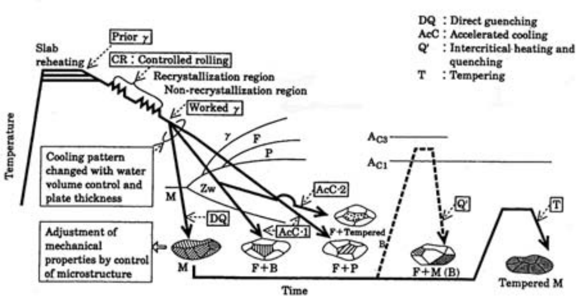

Fig.1 Schematic illustration of microstructure control on TMCP[4].

3. SUF steel

In rolling and cooling of heavy plates, there are non-uniform distributions of deformation, temperature and cooling rate between the surface and center, which can result in the difference of microstructure and the mechanical properties along the cross section.

Figure 2 shows the macrostructure of the SUF steel plate together with the microstructures of the surface layers and midsection regions[5]. The ultra-fine-grained region is the black layer observed at the surface of the steel plates. The average grain size in the surface layer is less than two micrometers. In the surface layer, the grain sizes are

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relatively homogeneous. The grain size changes significantly at the border of the surface layers and the mid-thickness of the plate.

The surface regions of the SUF steel fractured ductilely with plastic deformation which are called shear-lips, and these have a braking effect on unstable brittle crack propagation and further enhance the crack arrestability of the steel plate as shown in **Fig.3** 6).

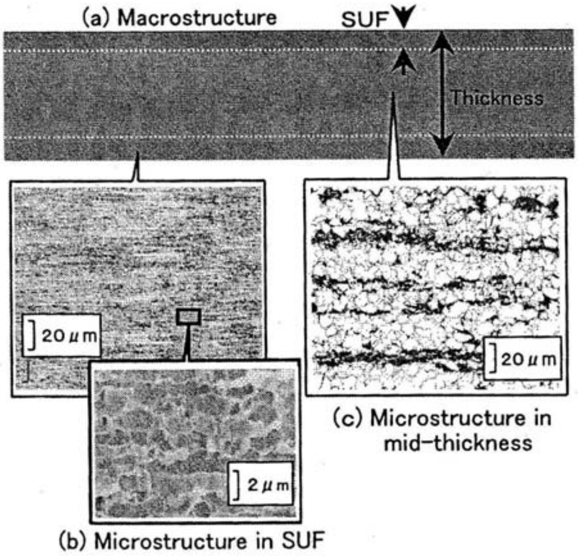

Fig.2 Macro and microstructures of a SUF steel plate5).

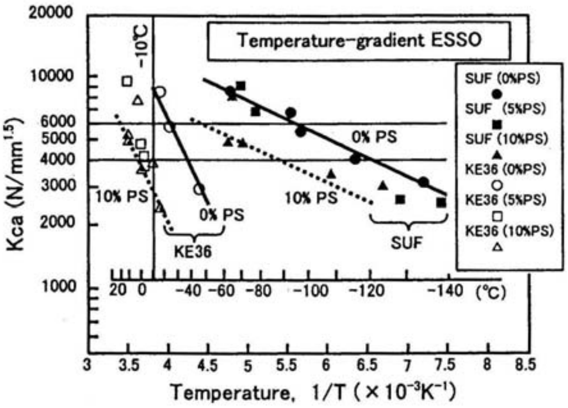

Fig.3 Effect of plastic strain on crack arrestability in SUF and KE36 steel plates (Plate thick: 25mm) 6).

4. Improvement of fatigue strength

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 mainly carried out from the viewpoint of structural design. These have been studied from the materials viewpoint, because it is well known that the fatigue strength of welded joints converge in limited ranges regardless of material strength.

A new dual phase steel which has excellent fatigue properties was developed. **Figure 4** shows the effect of the grain boundary between the hard phase (i.e. bainite) and the soft phase (i.e. ferrite) on fatigue crack growth behavior7). Detour and arrest of a fatigue crack are observed along its path.

The fatigue crack growth rate was decreased drastically when the crack proceeded to the surface of the bainite layer from the ferrite layer as shown in **Fig.5**.

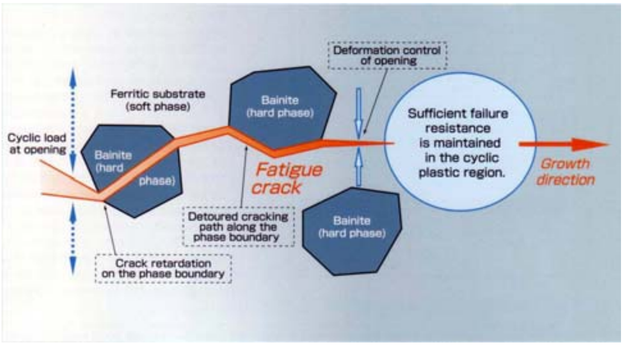

Fig.4 Schematic diagram showing the mechanism for improving fatigue performance in FCA steel7).

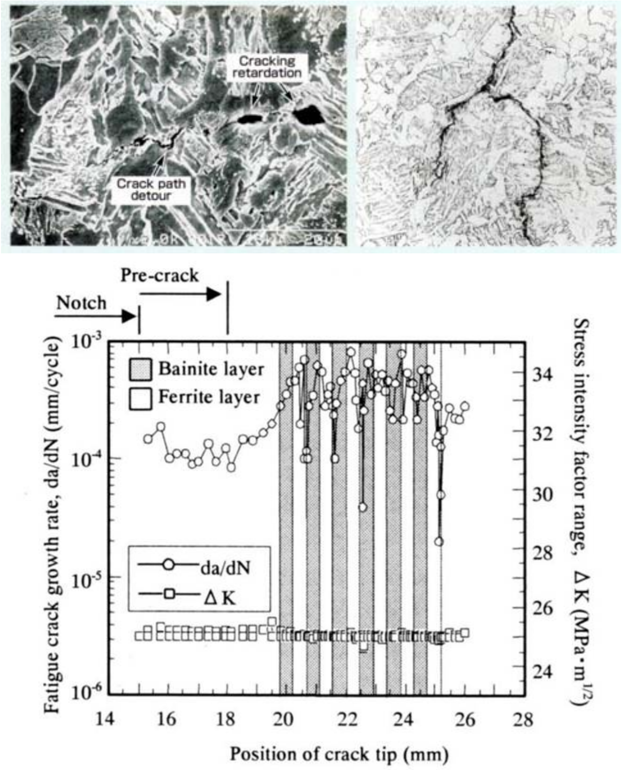

Fig.5 Effect of grain boundary between hard phase and soft phase on fatigue crack growth behavior7).

It has been shown that the low-temperature transformation welding consumable that contains large amount of Cr and Ni can bring compressive stress into weld toes (see **Table 1** and **Fig.6**) and is expected to improve the fatigue strength of welded joints of high strength steel plates8,9). This welding wire induces the compressive residual stress at the toe of weld and it enhances the fatigue strength of welded joint.

Table 1 Chemical composition, yield strength and transformation properties of materials8).

Material	Chemical composition (wt %)								Yield strength (MPa)	Transformation properties	
	C	Si	Mn	Ni	Cr	Mo	V	Fe		Temperature Ms(℃)	Strain ε f(%)
10Cr-10Ni	0.025	0.32	0.70	10.0	10.0	0.13		Balance	708	180	-0.55
KC60	0.07	0.49	0.96			0.42		Balance	579	450	0.23
KM80	0.06	0.20	1.21	2.66	0.80	0.48		Balance	760	444	-0.02
HT580	0.14	0.31	1.41	0.05	0.04	<0.01		Balance	497	460	0.06
HT780	0.10	0.17	0.85	1.25	0.48	0.50	0.035	Balance	821	440	0.05

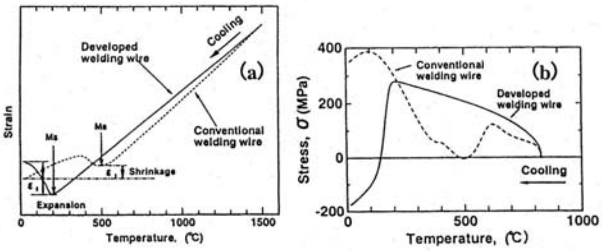

Fig.6 Variation of stress or strain in welding consumable with cooling of temperature. (a)Free deformation condition, (b)Strain constrained condition9).

5. Improvement of HAZ toughness

One of the notable progresses in welding technologies for shipbuilding in the early days was the development of one-side submerged arc welding for the fabrication of the hull. This improved the construction efficiency significantly in comparison with double-sided welding. Typical cross section of the weld is shown in **Fig.7** 10) along with a schematic of weld assembly of FCB as an example of one-side one-pass Submerged Arc welding. However, these high efficiency welding methods also involve an increase in heat input over the conventional double-sided welding. Therefore, the change of the welding method was put forward with the development of steels with improved HAZ toughness under high heat input welding.

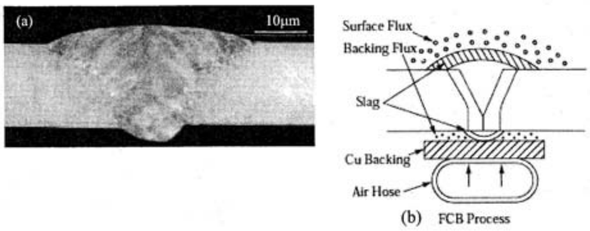

Fig.7 (a)Typical cross section of one-side one-pass SA weld, and (b)weld assembly of FCB welding as an example of one-side SA welding10).

Two approaches have been mainly employed to refine the microstructure of the coarse-grained heat-affected-zone (CGHAZ). One is the refinement of prior austenite grain size, which consequently refines the product phases, ferrite and bainite, transformed from the austenite. The other is the promotion of fine intragranular ferrite (IGF) nucleation in austenite.

It is well known that fine TiN particles in steel suppress the austenite grain growth and refine tha HAZ microstructure11-13). However, in the coarse grain HAZ adjacent to the fusion line, most of the TiN particles dissolve and lose their effect. The dissolution of TiN particles in the coarse grain of the HAZ is minimized by increasing the thermal stability of TiN particles in the austenite matrix as shown in **Fig.8** 14).

Figure 9 14) shows the effect of nitrogen content on TiN particles in a simulated HAZ with Tp=1400℃, Δt8/5=40 sec. Low nitrogen steels had a small number of large TiN particles, whereas high nitrogen steels had a large number of fine TiN particles size of 10 to 20 nm.

Figure 10 shows the HAZ microstructure of an SA weldment in conventional and high nitrogen TiN steels. The width of coarse grain HAZ in high nitrogen steel was measured as 0.2 mm wide and this is about 1/10 of coarse grain HAZ width of conventional steel. The austenite grains decreased with increasing nitrogen content. In particular, austenite grain refinement occurred significantly in TiN steels with more than 0.01 nitrogen content.

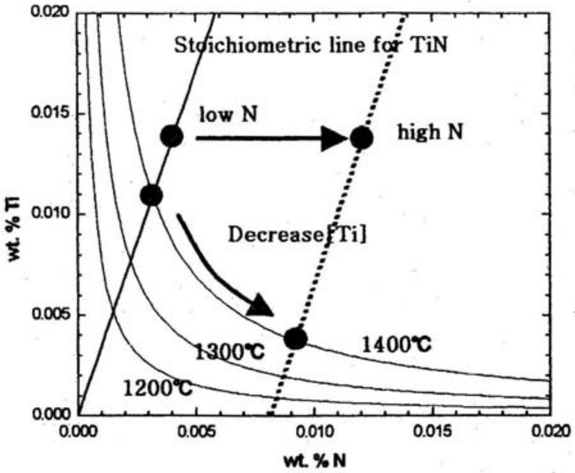

Fig.8 Thermal stability of TiN particles14).

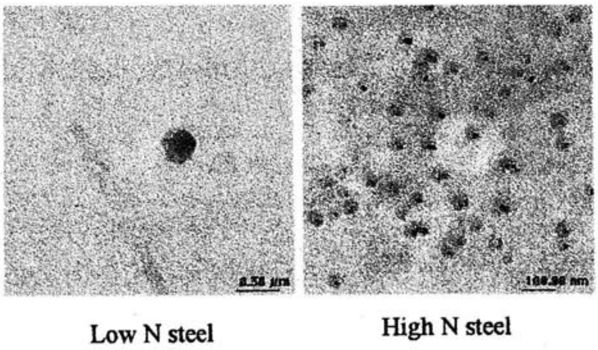

Fig.9 Effect of nitrogen content on TiN particles in simulated HAZ14).

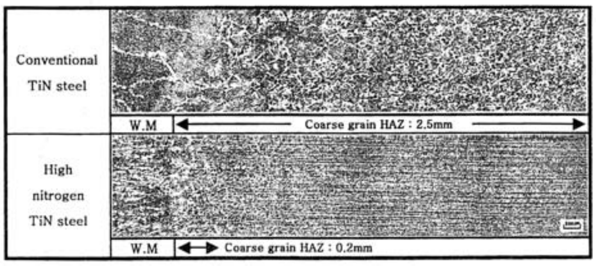

Fig.10 HAZ microstructure of SA weldment in conventional and high TiN steel[14)].

The dissolution of TiN, which has rather high solution temperature, is inevitable in the vicinity of the fusion line, and free N is generated. On the other hand, the B diffuses from weld metal to the HAZ because the consumables for high heat input welding have rather high contents of B. The diffusible B, as well as the B added to the base steel, combines with the free N during the welding thermal cycle, and the nucleation site for intragranular ferrite (IGF) increases, and the free N in the HAZ decreases. **Figure 11** [15)] shows the dissolution of TiN and diffusion of B from weld metal near the fusion line schematically.

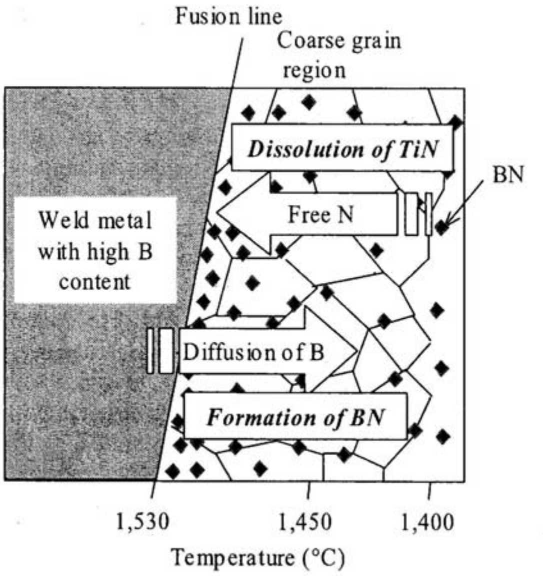

Fig.11 Schematic diagram of dissolution of TiN and diffusion of boron near fusion line[15)].

Ti-oxide, as a part of "oxide-metallurgy", is also a strong intragranular ferrite nucleation agent. TiN particles which have been widely used for suppressing grain boundary migration as a pinning effect, are dissolved if exposed for long period at high temperature like that of the fusion boundary of a high-heat-input weld HAZ. On the other hand, the oxide is very stable even at high temperature. To disperse the oxides of interest in steel plates, different deoxidizing elements were added during the refining and casting processes of steel making, and among the oxides dispersed, titanium oxides[16)] and rare-earth metal (REM) oxides[17)] were found to work as a nucleant of IGF in CGHAZ. **Figure 12** shows the intragranular ferrite initiated from Ti-oxide particle[16)]. HAZ toughness of TiO steel was much stable than that of TiN steel as shown in **Fig.13**.

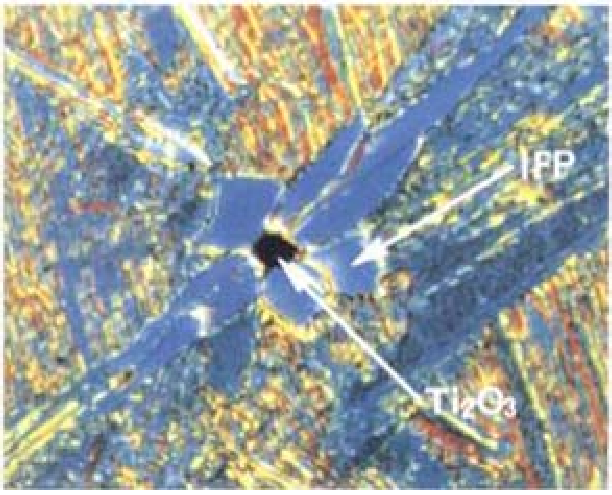

Fig.12 Intragranular ferrite (IGF) initiated from Ti-oxide particle[16)].

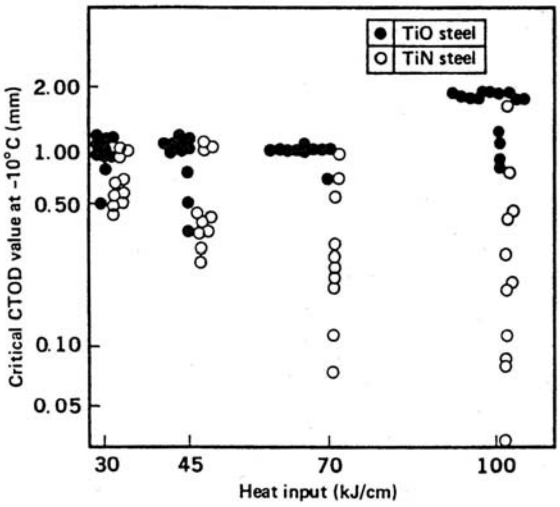

Fig.13 CTOD properties of the HAZ in TiO steels compared with TiN steels[16)].

Although oxide is very stable even at high temperature, it was difficult to finely disperse it. To overcome these contradictory natures, a new kind of particle in steel (Mg-containing oxide) was proposed (HTUFF steel) as shown in **Fig.14** [18)]. Changes in the size and number density of inclusions are depicted with respect to Mg content as shown in **Fig.15** [19)]. It is also described that Mg additions reduce the size and increase the number density of inclusions. Increase of number density should be noted since inclusions are potential nucleants for IGF formation.

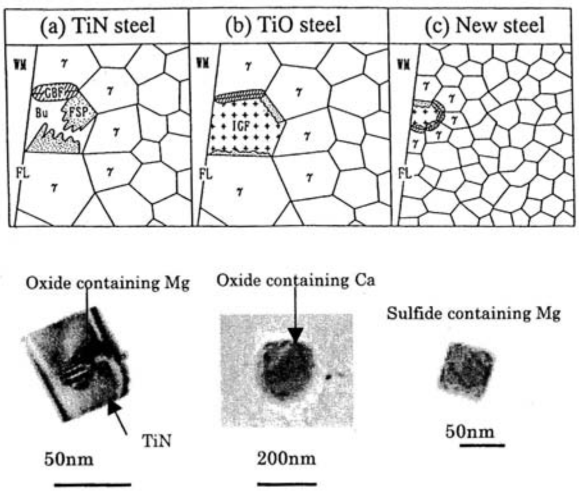

Fig.14 HTUFF steel with Mg-containing oxide[18).

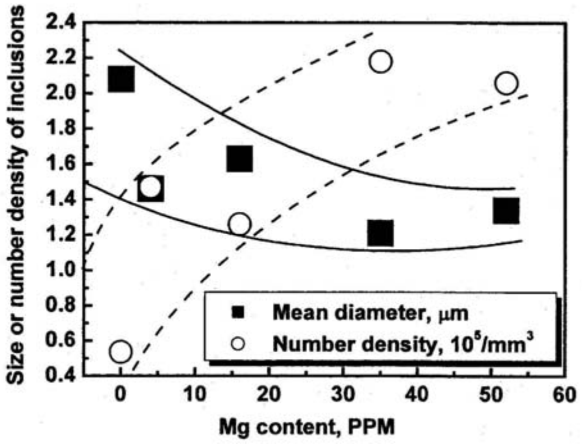

Fig.15 Changes in the size and number density of inclusions with respect to Mg content[19).

6. Development of new steel plates for shipbuilding

In recent years, more attention has been paid to the safety and durability of ships and environment protection of sea, which have led to the development of new structural steel plates. One of them is the development of more corrosion resistant plates for double-hull tankers. Crude oil carriers are now required to have double hulls to prevent oil spill, and an increase in temperature in oil tanks with the double hull structure increases the likelihood of corrosion of upper deck steel plates exposed to the vapor space in the tanks. To prevent the corrosion and to increase the lifetime of the ships, different corrosion resistant steel plates have been developed[20,21).

The development of new steel plates has also been made to increase construction efficiency and thereby to decrease construction cost. Longitudinally profiled (LP) steel plates were developed in this context[22). Thickness change within a plate was achieved by controlled rolling, which made it possible to replace the plates which had been made by welding steel plates of different thickness, and therefore to reduce the welding time and cost.

Another development is concerned with residual stress retaining in steel plates. TMCP steel plates are likely to possess residual stresses from their production, and this often results in distortion in different ways after cutting and welding of the plates. In order to achieve residual stress-reduced steel plates, temperature differences over the large surface area in a wide and long plate and through the thickness should be minimized and cold levering is also used for the purpose of reducing inhomogeneous stress for block shape accuracy[23).

A number of research projects are currently being carried out on European and national levels to improve the application of lasers and optical technologies in shipbuilding as shown in **Fig.16** [24). In laser beam welding, centre line solidification cracks in the fused zone are an issue and can limit the travel speed and, hence, productivity. The fused zones are typically of the same composition as the steel being welded and whilst there are several welding procedural factors which can be used to minimize the risk of cracking, the problem hinges on the steel composition. Lower S and P levels may thus be required as shown in **Table 2** [25).

Fig.16 High powered Laser applications in shipyard industry[24).

Table 2 Classification society guidelines for laser welding of ship hull(1996) [25).

C	0.12% max	(lower speeds ≤ 0.15%)
S	0.005% max	(≤ 0.010% for ≤ 12mm, 0.6m/min)
P	0.010% max	(≤ 0.015% for ≤ 12mm, 0.6m/min)
CE	0.38% max	
Weld hardness≤380 HV5 max		(≤400 HV5 isolated)

7. Summary

Most steelmakers are increasingly working with the joining community so that welding issues are being assessed early in the development program. In summary, although a lot of progress has been made over the last thirty years in steel plates and welding technology for shipbuilding, there are still growing demands from the view of energy transport, logistics, safety, environment and so on.

References

1) C.Shiga, K.Amano, T.Enami, M.Tanaka and R.Tarui: Proc. Int.Conf. on Technology and Application of HSLA Steels, (1984), pp.643-649

2) M.Tada and K.Hirota: Bulletin of ISIJ, 10-12(2005), pp.924-928
3) T.Koseki: Proc. Asia Steel 2006, Fukuoka, May 2006, pp.128-133
4) K.Ohsawa: Tetsu-to-Hagane, 81-4(1995), pp.449-454
5) T.Ishikawa, Y.Nomiyama, I.Hagiwara and S.Aihara: J. Soc. Naval Architects of Japan, No.117(1995), pp.259-267
6) T.Ishikawa and T.Inoue: Proceedings of ICASS 2002, May 2002, pp.91-92
7) N.Konda, K.Arimochi, K.Fujiwara, A.Nagayoshi, A.Inami, M.Yamashita and H.Yajima: J. Soc. Naval Architects of Japan, No.190(2001), pp.507-515
8) A.Ohta, O.Watanabe, K.Matsuoka, C.Siga, S.Nishijima, Y.Maeda, N.Suzuki and T.Kubo: Quarterly J. Japan Welding Society, Vol.18, No.1(1999), pp.141-145
9) A.Ohta, K.Matsuoka, N.T.Nguyen, Y.Maeda and N.Suzuki: Welding Journal, 82(2003), pp.77s-83s
10) K.Nagatani and M.Komura: R&D Kobe Steel Engineering Report, 50-3 (2000), pp.70-75
11) S.Kanazawa, A.Nakajima, K.Okamoto and K.Kanaya: Tetsu-to-Hagane, 61(1975), pp.2589-2595
12) S.Ueda, M.Ishikawa, K.Kobayashi and T.Funakoshi: Tetsu-to-Hagane, 61(1975), S598
13) S.Matsuda and H.Kageyama: Tetsu-to-Hagane, 61(1975), S257
14) H.C.Jeong, Y.H.An and W.Y.Choo: Fifth Workshop on the Ultra-Steel, Jan. 2001, pp.224-225
15) S.Suzuki, K.Ichimiya and Y. Kitani: Asia Steel International Conference 2006, May 2006, pp.746-751
16) K.Yamamoto, S.Matsuda, T.Haze, R.Chijiiwa and H.Miura: ASTM-STP 1042, ASTM, Philadelphia, (1989), pp.266-271
17) T.Funakoshi, T.Tanaka, S.Ueda, M.Ishikawa, N.Koshizuka and K.Kobayashi: Tetsu-to-Hagane, 63(1977), pp.303-309
18) A.Kojima, R.Uemori, M.Minagawa, M.Hoshino and K.Ichikawa: Materia, Vol.42, No.1(2003), pp.67-69
19) H.S.Kim, C.H.Chang and H.G.Lee: 7th Workshop on the Ultra-Steel, June 2003, pp.284-285
20) K.Inoue, T.Oshima, A.Yonezawa, T.Imai, K.Katou and Y.Usa: Techno Marine, 878(2004), pp.201-206
21) K.Kashima, H.Miyuki, H.Katsumoto and A.Inami: J. Society of Naval Architects, 5(2005), pp.131-136
22) Y.Yuge, T.Hori and S.Nishikawa: Kawasaki Seitetsu Giho, 30(1998), pp.137-142
23) T.Tani, Y.Kobayashi, K.Ohe, T.Ueda, N.Okada and T.Miyazaki: R&D Kobe Steel Engineering Report, 52-1 (2002), pp.6-10
24) Home page of TRUMPF
25) Classification Societies ‘Guidelines for the approval of CO2 laser welding’ in Select Int. Conf. on “Exploitation of laser processing in shipyards and structural steelwork”, TWI, Cambridge, May 1996.