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Steel Plates for Bridge Use and Their Application Technologies†

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Abstract:

Essential steel plates for bridge use of JFE Steel are reviewed together with relevant key-technologies. Owing to Super-OLAC that realizes an ultimate theoretical cooling rate, high performance steels such as a TS 570 N/mm^2 class ones and weathering steels with a low P_{CM} value are materialized by efficient on-line process which offers a short delivery time and saving in welding fabrication. As for weathering steel, two kinds of advanced Ni type are lined-up for various airborne salt environments. Also presented herein are new surface treatment technologies to promote protective rust formation for a better appearance of a bridge. Furthermore, longitudinally profiled (LP) steel plates are lined-up for welding labor and dead weight reductions and low transformation-temperature welding consumables are developed for remarkable fatigue strength of welded joints.

1. Introduction

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 increasingly important considerations. In responding to these needs, JFE Steel installed the *Super*-OLAC, a revolutionary on-line accelerated cooling device with a theoretical limit-equivalent cooling capacity, in its plate manufacturing process, realizing production of as-rolled high strength steel plates and plates with substantially improved weldability for bridge use. JFE Steel has also developed and commercialized weathering steels which greatly reduce bridge LCC, together with new rust stabilization treatment technologies which extract the maximum performance from such steels. 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 of using them which significantly improve the fatigue strength of the welded joint. Thus, JFE Steel has a comprehensive development program for steel plates for bridge use and related technologies and is continuing to expand product line in this field.

Among these efforts, this report describes 570 N/mm^2 class high performance, high strength steel with excellent weldability, which makes the maximum use of the functions of *Super*-OLAC, and two grades of Ni-added high corrosion resistance weathering steels, which can be used in the environment with airborne salt concentration exceeding 0.05 mdd (mg-NaCl/day/100 cm^2) such as on shore and in coastal areas where conventional JIS

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(Japanese Industrial Standard) weathering steels cannot be used without painting. Two types of new rust stabilization treatment technique, an ageing type and an accelerating one, are also introduced.

Longitudinally profiled (LP) steel plates are introduced by focusing mainly on proposals for effective use, and the outline of a technology for improving welded joint fatigue strength by using low transformation-temperature welding consumables is presented.

2. Steel Plates

2.1 High Strength Steel Plates with High Performance

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. In particular, with increasing use of high strength, heavy gauge plates, reduction or omission of preheating to prevent weld cold cracking had become an issue, considering the large man-hour burden of this work. Thus, the development of an “easy-to-use high strength steel” which would solve this dilemma was greatly desired. In responding to these needs, JFE Steel developed a wide range of high performance products, which are based on the controlled rolling technology, and high strength products, which utilize minimum carbon equivalent (C_{eq}) design, making full use of TMCP (thermo-mechanical control process) technology which combines controlled rolling and accelerated cooling in advance of other steel makers. Moreover, since 1998, JFE Steel has introduced a revolutionary *Super*-OLAC, which possesses a theoretical limit-equivalent cooling capacity, at its plate mills and other production lines, realizing a combination of controlled rolling and theoretical accelerated cooling. As a result, the company has achieved a substantially higher level of TMCP technology. Among new products, this technology enabled the development and commercialization of low C_{eq} high strength steel plates which have high yield strength combined with excellent weldability.

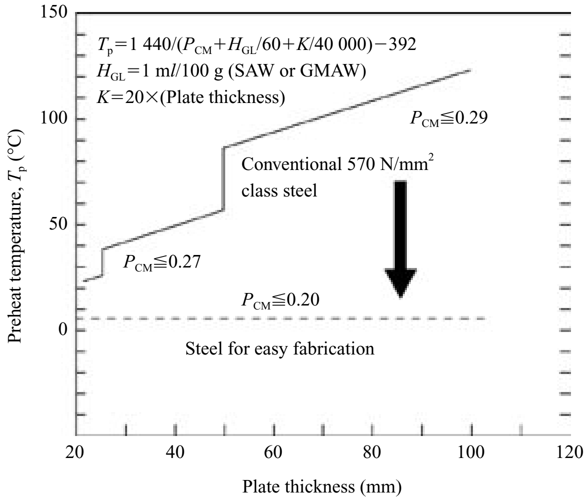


Fig. 1 Relation between plate thickness and preheat temperature for 570 N/mm^2 class steel

Preheating temperature can be effectively lowered by decreasing susceptibility to weld cracking, which is prescribed by chemical composition (P_{CM}). For example, **Fig. 1** exemplifies the relationship between the plate thickness and preheat temperature of 570 N/mm^2 class steel. The step-like solid line in the upper part of the figure shows the required preheat temperatures to various thickness of plates with the standard P_{CM} values as specified in “Specifications for Highway Bridges”. The application of low P_{CM} steel (P_{CM} ≦ 0.20), as shown by the broken limit line, makes it possible to eliminate preheating when the steel temperature is 10°C or higher, even for heavy gauge plates.

Table 1 shows the examples of mechanical properties of 570 N/mm^2 class steel plates with optimum balance of strength with toughness, which were commercialized by making the maximum use of TMCP technology for controlling hardenability with addition of micro-alloying elements. Steel B is also comprising the weathering property. In all cases, the steels have low P_{CM} values of 0.18 which is under 0.21, excellent weldability, and also have yield strength value higher than 500 N/mm^2. Both the base metal and the welded joint show high Charpy absorbed energy values. These excellent properties exceed those of the high performance steel HPS 485[1)] used in practical applications in the

Table 1 Examples of chemical composition and mechanical properties of steel plate produced by TMCP

Steel	Thickness (mm)	Chemical composition (mass%)									Mechanical properties						
											Base plate			Welded joint			
		C	Si	Mn	P	S	Cu	Ni	Cr	P_{CM} *2	YS (N/mm^2)	TS (N/mm^2)	vE−5 (J)	Welding method	Heat input (kJ/cm)	TS (N/mm^2)	vE−5 FL*3 (J)
A	75	0.08	0.25	1.42	0.007	0.002	–	–	–	0.18	534	626	312	SAW	46	632	141
B*1	50	0.08	0.20	0.88	0.008	0.002	0.34	0.16	0.55	0.18	521	620	308	SAW	67	626	151
C	50	0.02	0.23	1.97	0.009	0.002	0.41	0.42	0.49	0.21	710	845	234*4	GMAW	22	832	185*5

*1Weathering steel, *2P_{CM}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B, *3FL : Fusion line, *4vE−40, *5vE−15

United States.

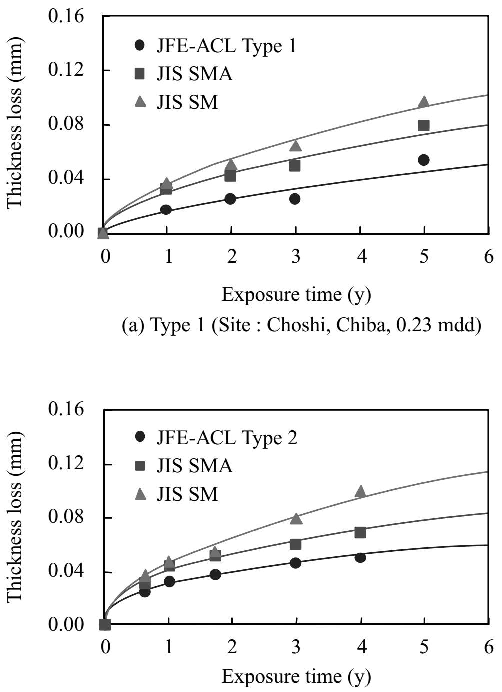
Using the transformation behavior distinctive to the bainitic structure of extremely low carbon steel with a carbon content less than approximately 0.02 mass%, JFE Steel has also completed commercialization of a 570 N/mm^2 class TMCP type, extremely low carbon bainitic steel plate of heavy gauge,[2)] which features small cooling rate dependency of the microstructure and material properties, as well as low welding hardenability at high strength level owing to an extremely low carbon composition. The extremely low carbon bainitic steel is delinered as an as-rolled product, so that it can be delivered in a short lead time and reached the strength of 780 N/mm^2 class (steel C).

2.2 Ni-added High Corrosion Resistant Weathering Steels

The conventional weathering steel, i.e. JIS SMA (Hot-rolled atmospheric corrosion resisting steels for welded structures), can be used without painting in regions where the amount of airborne salt is not more than 0.05 mdd, because more airborne salt makes it difficult to stabilize rust, as observed on shore and in coastal areas.[3)] JFE Steel developed and commercialized two grades of Ni-added high corrosion resistant weathering steels, which can be used without painting even in such environments with high airborne salt.

The Ni-added high corrosion resistant weathering steels "JFE-ACL Series" are micro-alloyed with Ni and Mo. Nickel has the following two revealed effects: (1) suppressing water permeability through refinement and densification of the rust layer and (2) electrochemically blocking the penetration of Cl ion by increasing the pH of the rust layer.[4)] Mo also has the effect (2). On the basis of the outdoor exposure tests and the cyclic corrosion tests, revealed that the addition of Ni in the range of 1.0 to 3 mass%, and Mo: 0.2 to 0.6 mass%, is effective in the airborne salt environment described above, also securing mechanical properties and weldability.

Table 2 shows the examples of chemical composition and mechanical properties of JFE-ACL Series. For Type 1, Mo is added up to the effective upper limit of 0.3% in case of combination with 1.5% Ni. For Type 2 (ultra-low C basis), Ni is added to the effective upper limit to secure corrosion resistance against higher concentration of airborne salt than Type 1. For both Type 1 and Type 2, a full range of 400 N/mm^2, 490 N/mm^2, and 570 N/mm^2 products have been developed. In terms of mechanical properties and weldability, all grades offer performance equal or superior to that of JIS SMA. Atmospheric corrosion resistances of JFE-ACL 490 Type 1 and Type 2 were evaluated in a seaside exposure test, as shown in **Fig. 2**(a) and (b). For Type 1, the exposure site was Choshi, Chiba Pref., where the annual average of airborne salt is 0.23 mdd, whereas the site was Gunshigawa, Okinawa Pref. (0.80 mdd) for Type 2. Both



(a) Type 1 (Site : Choshi, Chiba, 0.23 mdd)

(b) Type 2 (Site : Gushikawa, Okinawa, 0.80 mdd)

Fig. 2 Exposure test results of various steels at coastal areas

Table 2 Examples of chemical composition and mechanical properties of Ni added weathering steel

Steel	Thickness (mm)	Chemical composition (mass%)										Mechanical properties				
		C	Si	Mn	P	S	Cu	Ni	Mo	C_{eq} *1	P_{CM} *2	YS (N/mm^2)	TS (N/mm^2)	El (%)	$_vE_0$ *3, $_vE_{-5}$ (J)	vTs (°C)
JFE-ACL400 Type 1	12	0.04	0.30	0.57	0.032	0.003	–	1.42	0.30	0.27	0.13	291	460	34	373	−59
JFE-ACL490 Type 1	50	0.07	0.32	0.71	0.033	0.002	–	1.45	0.32	0.33	0.16	358	515	38	281	−43
JFE-ACL570 Type 1	75	0.07	0.26	0.74	0.029	0.004	–	1.48	0.31	0.32	0.16	532	625	32	270	−50
JFE-ACL400 Type 2	50	0.02	0.27	0.32	0.011	0.003	0.37	2.60	–	0.15	0.10	355	460	40	355	−35
JFE-ACL490 Type 2	50	0.02	0.29	0.92	0.006	0.005	0.37	2.68	–	0.26	0.14	445	528	39	388	≦−80
JFE-ACL570 Type 2	50	0.02	0.34	0.98	0.013	0.002	0.39	2.61	–	0.27	0.14	523	637	32	390	≦−80

*1 C_{eq} = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14, *2 P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B,
*3 ACL400 Type 1, ACL490 Type 1, ACL400 Type 2, ACL490 Type 2, *4 ACL570 Type 1, ACL570 Type 2

Type 1 and Type 2 steels showed corrosive thickness loss smaller than JIS SMA and JIS SM, demonstrating that these new steels have excellent atmospheric corrosion resistance.

A general guideline for use without painting is "the corrosive thickness loss of 0.5 mm or less in 100 years."[5] Judging from the results of simulated exposure test conducted in bridge environments at various sites in Japan,[6] and the above guideline, it is conservatively possible to use JFE-ACL Series without painting in the environment with salt levels of 0.4–0.6 mdd. More accurate fit-to-environmental judgement is expected to make these steels in use in areas with higher amount of airborne salt.

2.3 New Rust Stabilization Treatments

JFE Steel has developed and commercialized 2 types of new rust stabilizer, an ageing type which forms a protective rust film on the steel surface, called "CUPTEN COAT M",[7] and an accelerating type, called "e-RUS®".[8]

CUPTEN COAT M was advanced from JFE Steel's popular CUPTEN COAT (2-layer type), which had been applied to more than 600 actual cases. Among the practical ageing types, the single-layer treatment agent, CUPTEN COAT M, has an excellent ease-of-use. Rust flaking are prevented by adding to the treatment film a substance which reacts selectively with Fe ions, and an appropriate wet-and-dry condition under the film is maintained by increasing water and oxygen permeability into the film to promote forming of the protective rust film. As illustrated in **Fig. 3**, the film also has a Cl ion permeation suppressing function due to electrical repulsion made by an anion type resin.

The e-RUS utilizes the revealed phenomenon in which rust tends to form more easily when the same type of rust is already present at the time of rust formation. Thus, this accelerating type comprises 2-layers of stabilizer. Particles of fine artificial rust are composed in the film as nucleation site of protective rust, promoting speedy formation of a protective rust film. The bottom layer of the film contains butyral, which has high water and oxygen permeability and promotes protective rust formation. Molybdate, which is also added to the top layer, the finishing film, has a function of suppressing Cl ion permeation owing to the electrical repulsion to the film and the formed protective rust layer, as shown in **Fig. 4**.

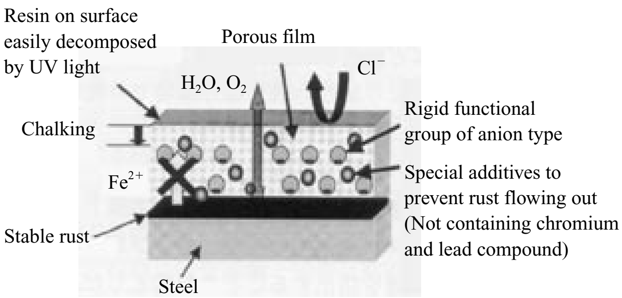


Fig. 3 Function of CUPTEN COAT M on weathering steel

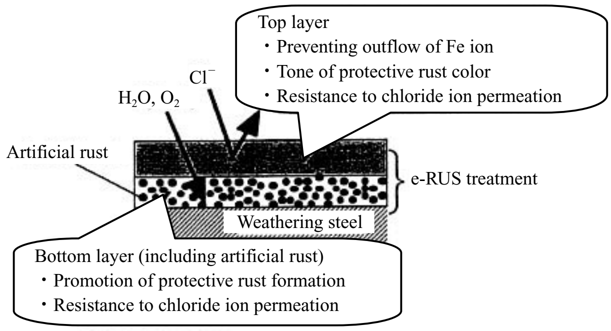


Fig. 4 Function of e-RUS on weathering steel

The stabilizers of both CUPTEN COAT M and e-RUS are adaptive either to a bridge works factory coating or to a site coating. A great advance of these two stabilizers is that they can be coated in a plate production line before shipment and has a primary rust-preventive functing while in storage in a similar manner to popular shop primers. As a result, finish coating requires only simple material surface preparation and saves shot-blasting time in which normally needs a high man-hour burden and thus rises total construction cost.

The CUPTEN COAT M and e-RUS treatment can perform in coastal areas with adaptive weathering steels such as Ni-added high atmospheric corrosion resistance steels described in the previous section. Moreover, they have an additional advantage of eliminating attacks to emvironment, because these stabilizers are free from chromium and lead compounds.

2.4 LP Steel Plates for Bridge Use

Longitudinally profiled (LP) steel plates[9] are plates in which the plate thickness varies lineally in the longitudinal direction by precise and continuous roll gap control. The LP plates have high performance in reducing the number of welds and the weight of steel in structures.

A variety of 8 profiles are available to LP plates. The fundamental type is LP1, whose thickness is changed simply over the whole plate length at a same inclination. The variation includes convex-shaped LP3, concave-shaped LP5, and LP7 which features a 2-step thickness change. For ease of joining, LP plates can have a constant-thickness part at the head and/or tail end. The expected benefits of LP plates include (1) rational plate thickness design, corresponding to meet cross-sectional primary moment and weight reduction, (2) rational girder design, such as equal flange width, (3) elimination of the filler plates at bolt connections, and (4) elimina-

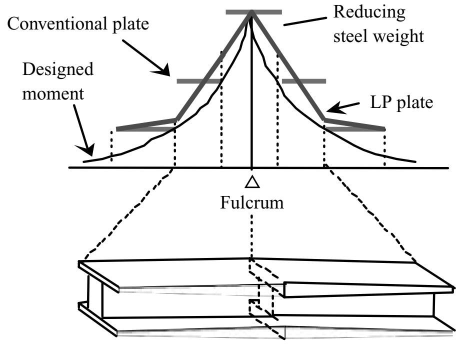


Fig. 5 Comparison between an LP plate moment and an isometric plate moment against a designed moment in a girder of bridge

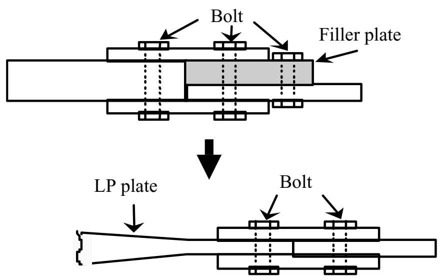


Fig. 6 Example of omission of filler plate in connected parts

tion of plate thickness adjustment machining at welded joints. LP plates can be applied to all the JIS specified steel product in Specifications for Highway Bridges, including quenching and tempered steels and TMCP steels.

Two examples of effective application of LP plates[10] are demonstrated in **Figs. 5** and **6**. The LP plates were applied to the flanges of a bridge girder placed at an intermediate fulcrum point in Fig. 5. The use of LP plates makes it possible to change the plate thickness rationally, and reduce the steel weight and the number of welds in comparison to the use of isometric plates. Figure 6 shows the case of a bolt connection application. Although the use of a filler plate is usual to eliminate the difference in joint thickness in case of isometric plates, the LP plates can eliminated the filler plate, and the number of bolts can have also been reduced simultaneously.

In addition to highly accurate dynamic thickness control and controlled cooling technologies, which are the basis of the manufacturing process, advanced leveling technology and dimensional inspection methods, etc. developed exclusively by JFE Steel are used in manufacturing LP plates. For example, the cooling rate is kept constant for plate thickness change by applying accurate transfer control during cooling in TMCP.

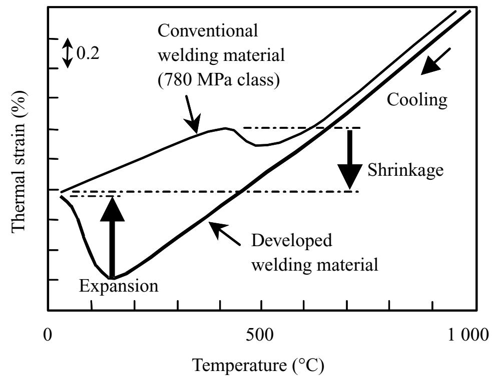


Fig. 7 Relation between thermal strain and temperature of welding material

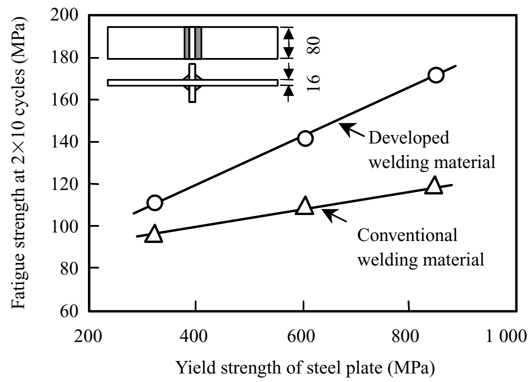


Fig. 8 Relation between fatigue strength of welded joint and yield strength of steel plate

3. Technology for Improvement of Fatigue Strength of Welded Joint

Since welding tensile residual stress normally reduces the fatigue strength of weld below that of the base metal, the fatigue strength of welded joint is substantially independent of base metal strength. This long-lasting problem was solved through the development of a 10%Cr-10%Ni-Fe type low transformation-temperature welding consumable, "EXWEL", in which the martensite transformation initiation temperature is greately reduced to below that of conventional welding consumables by generating compressive residual stress in the weld, as shown in **Fig. 7**.

The fatigue strength of a non-load-carrying cruciform welded joint using the developed welding consumable significantly increases in proportion to the increased base metal strength, as shown in **Fig. 8**.[11] Since the extended application of high strength steel and the requirements of higher fatigue safety for structures are expected in the future, JFE Steel is accelerating the study of this technology aiming at practical application.

4. Conclusions

The current status of the development and commercialization of key steel plates for bridges at JFE Steel has been described. JFE Steel is confident that it can contribute to the construction of bridges with high asset value by supplying high strength steels with high performance produced using its unique *Super*-OLAC accelerated cooling technology, Ni-added high atmospheric corrosion resistance steels which can withstand environments with airborne salt concentrations exceeding 0.05 mdd and new rust stabilizers, and LP plates. The company also believes that dramatically improved safety can be achieved in steel bridges by applying next-generation technologies such as welded joint fatigue strength improvement using low transformation-temperature welding consumables.

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