Development of YP 960 and 1 100 MPa Class Ultra High Strength Steel Plates with Excellent Toughness and High Resistance to Delayed Fracture for Construction and Industrial Machinery†

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Abstract:

Construction and industrial machinery has grown in size and is now being used in increasingly severe environments. These changes are fueling growing needs in the market for ultra high strength steel plates with excellent toughness. To meet these needs, JFE Steel has developed two new types of ultra high strength steel plate with excellent toughness for construction and industrial machinery: JFE-HYD®960LE and JFE-HYD®1100LE. The main characteristics of the material design applied to these new steels are refinement of the effective grain and enhancement of the uniform dispersion of fine cementite, which are achieved by ausforming and rapid heating and tempering. Ausforming is achieved by quenching the work-hardened austenite. The uniform dispersion of fine cementite, meanwhile, is realized by rapid heating and tempering using HOP® (Heat-treatment On-line Process), the only technology of its kind in the world. Due to this material design, these newly developed steels have high resistance to delayed fracture as well as excellent low temperature toughness. The high resistance to delayed fracture is one of the most important characteristics to utilize these ultra high strength steels for industry. JFE-HYD960LE and JFE-HYD1100LE also have excellent weldability due to the low carbon content and low carbon equivalent design. These steels are already in use in global industries and we expect the demand for them to grow as the needs for large construction and industrial machinery expand in the future.

1. Introduction

Construction and industrial machinery such as lattice boom crawler cranes, all terrain cranes and the like are growing in size and being deployed in increasingly severe environments. As a consequence, the market needs for ultra high strength steel plates with excellent toughness have recently been growing. On the other hand, toughness, weldability and delayed fracture resistance generally deteriorate as steel materials are strengthened. The market thus has expected the development of ultra high strength steel plates with excellent low temperature toughness, excellent weldability and high resistance to delayed fracture.

To meet these market needs, JFE Steel has developed JFE-HYD®960LE and JFE-HYD®1100LE[1,2], two new types of ultra high strength steel plate with excellent toughness and high resistance to delayed fracture for application in construction and industrial machinery.

The newly developed HYD960LE and HYD1100LE have minimum yield strengths of 960 MPa and 1 100 MPa, respectively. The main characteristics of the material design applied to these new products are refinement of the effective grain and enhancement of the uniform dispersion of fine cementite by ausforming and rapid heating and tempering. Due to this material design, the newly developed steels show excellent low tempera-

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ture toughness and guarantee Charpy impact energy at −40°C and also have high resistance to delayed fracture[3)] that is one of the most important characteristics to utilize these ultra high strength steels for industry. Furthermore, the developed steels show excellent weldability due to the low carbon content and low carbon equivalent design.

This paper introduces the characteristics of the newly developed technologies used for the manufacture of these new steels: the ausforming technology and the rapid heating and tempering technology and then describes the mechanical properties of the developed steels.

2. Characteristics of the Newly Developed Technologies

2.1 The Mechanical Properties Targeted and the Concept behind the Material Design

Table 1 shows the mechanical properties targeted for the YP960 and YP1100 MPa class ultra high strength steel plates for construction and industrial machinery. The guaranteed Charpy impact energy at −40°C, for example, was set at a 27 J minimum in consideration of use in cold regions.

High strength steel plate with tensile strength of 600 MPa class or over is generally manufactured by quenching and tempering. Two processes are available for the quenching: reheat quenching and direct quenching. In the case of reheat quenching, the steel plates are rolled, air-cooled, reheated to the austenite region and then quenched. In the case of direct quenching, the steel plates are quenched directly after rolling.

Figure 1 shows the relationship between the carbon equivalent and strength of reheat quenched steels and directly quenched steels. The directly quenched steels have higher strength than the reheat quenched steels under the same carbon equivalent conditions. One of the

Table 1 Mechanical properties targeted for YP960 and 1 100 MPa class ultra high strength steel plates for construction and industrial machinery

Grade	Thickness (mm)	Tensile properties			Charpy impact properties	C_{eq}***** (%)
		YS* (MPa)	TS** (MPa)	El*** (%)	$_vE_{-40°C}$**** (J)	
HYD960LE	12.0–32.0	≧ 960	980–1 150	≧12	≧27	≦0.64
HYD1100LE	12.0–32.0	≧1 100	1 180–1 500	≧12	≧27	≦0.70

*Yield strength **Tensile strength ***Elongation
****Absorbed energy at −40°C
*****Carbon equivalent=C+Mn/6+(Cu+Ni)/15+(Cr+Mo+V)/5

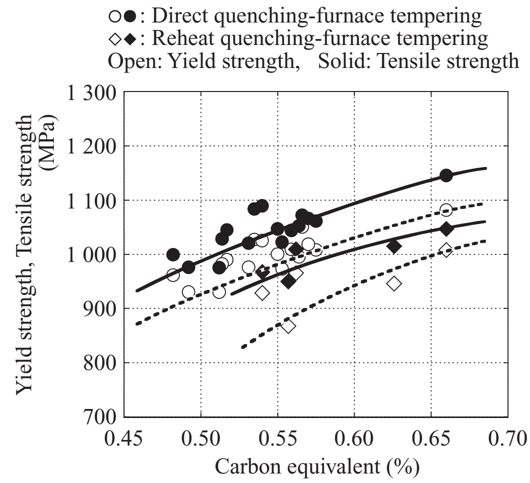

Fig. 1 Strengthening of steel by direct quenching

causes of this strength differential is the higher heat temperature of the directly quenched steels. The higher heat temperature leads to a homogeneous dissolution of alloy elements, especially carbo-nitride-forming elements, in austenite and improves the hardenability[4)]. The decrease in the carbon equivalent generally improves weldability and thus facilitates productivity in construction. In light of these advantages, direct quenching was applied for the quenching of the newly developed steels.

Directly quenched steels can be strengthened to maximal levels by ausforming[5,6)]. Ausforming is a thermo-mechanical treatment technology achieved by quenching the work-hardened austenite[5,6)]. Cellular dislocation is introduced in austenite by working. The inheritance of this cellular dislocation to martensite strengthens ausformed steels[7)], whereas toughness and elongation are little decreased by the refinement of the effective grain[6)].

The application of ausforming to steel plates has been reported earlier for HT950 steel for penstock use[8)], ausformed bainite[9)] and so on. In the case of HT950 steel, ausforming was applied to the surface part of heavy-walled high strength martensite steel to prevent the surface toughness from deteriorating. In the case of ausformed bainite, ausforming was applied to improve the toughness of TS600 MPa class steel with upper bainite microstructure. There have been no previous studies, however, on the application of ausforming to material designs for ultra high strength martensite steel plate with tensile strength of 980 MPa or over for application in construction and industrial machinery.

The material design of the newly developed steels uses ausforming technology to maximize the effects of direct quenching and thereby improve the strength and toughness balance.

The tempering of the steel plates, meanwhile, is generally performed with a furnace installed on the production line separately from the rolling and quenching processes.

JFE Steel recently developed the HOP®[10,11] (Heat-treatment On-line Process) to increase productivity and improve the mechanical properties of quenched and tempered steel plates. JFE Steel has deployed HOP on a practical basis for the first time in the world and has launched full-scale operation as of May 2004. This newly developed HOP applies induction heating and enables the continuous tempering of steel plates on the same production line as the rolling and quenching processes.

Rapid heating and tempering by HOP has already been used to manufacture steel plates with tensile strengths of 610–930 MPa class for tanks, construction and industrial machinery and so on[12–16]. The rapid heating and tempering technology by use of HOP improves the productivity and mechanical properties of these newly developed steels.

As mentioned above, the material design of the newly developed steels is mainly characterized by ausforming technology and rapid heating and tempering technology. These newly developed technologies realize excellent low temperature toughness, high resistance to delayed fracture and excellent weldability of the steels produced.

2.2 Fine Microstructure by Ausforming Technology

Ausforming effect is achieved by quenching work-hardened austenite, which is obtained by working austenite in the recrystallization region.

Figures 2 (a)–(d) show optical micrographs etched by picric acid and the results of orientation measurement by the electron back scattering pattern (EBSP) method. The samples used were YP960 MPa class steels. The finishing rolling temperatures of these materials were 924°C and 782°C. The finishing rolling temperature is defined as the temperature at which a material is rolled for the last time in the rolling process. The upper limit temperature of the non-recrystallization region of this material is 920–940°C. Hence, the material was mainly rolled in the recrystallization region of austenite when the finishing rolling temperature was 924°C and rolled in both the non-recrystallization and recrystallization regions when the finishing rolling temperature was 782°C. The expansion of the prior austenite grain was greater and the microstructure was more refined when the finishing rolling temperature was adjusted downward from 924°C to 782°C.

Figures 2 (e) and (f) show the relationship between the finishing rolling temperature and mechanical properties. Steel plates were heated at a rapid heating rate and tempered at 640°C. These figures show an improvement in the low temperature toughness and an enhancement in strength as the finishing rolling temperature was adjusted downward. This improvement in the strength and toughness balance may be attributed to the increase in the dislocation density and the refinement of the effective grain through the ausforming effect.

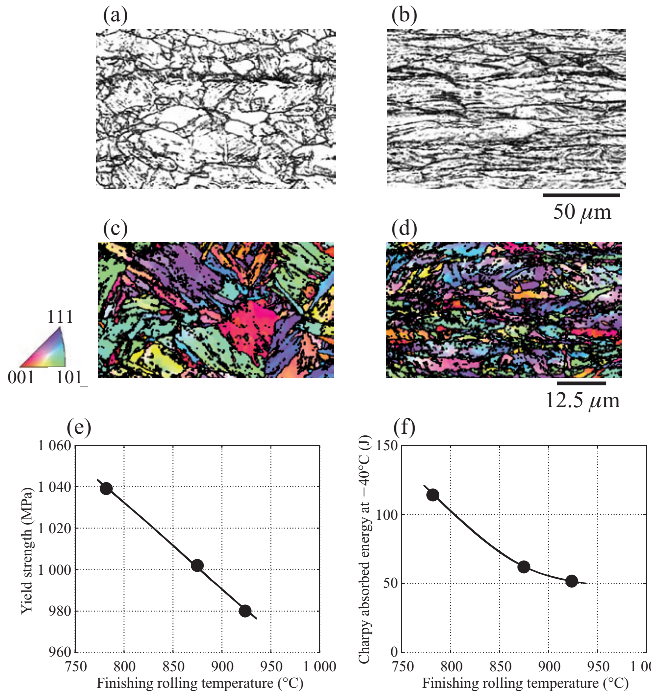

Fig.2 Effects of ausforming on microstructure and mechanical properties of HYD960LE steel: (a), (b) Optical micrographs, picric acid etching; (c), (d) EBSP images; Finishing rolling temperature of (a), (c) is 924°C and that of (b), (d) is 782°C

2.3 Uniform Dispersion of Fine Cementite by Ausforming Technology and Rapid Heating and Tempering Technology

Cementite acts as a brittle fracture origin[17] and hydrogen trapping site[18]. The cementite morphology, therefore, may have a great effect on low temperature toughness and delayed fracture resistance. Hence, uniform dispersion of fine cementite was studied in detail to improve the low temperature toughness and the delayed fracture resistance.

Figure 3 shows TEM micrographs of carbon extraction replicas made from three kinds of YP1100 MPa class steel. The first steel was rolled in the recrystallization region, quenched and tempered at a heating rate of 0.3°C/s. The second steel was rolled in the non-recrystallization region to achieve the ausforming effect, quenched and tempered at a heating rate of 0.3°C/s. The third steel was rolled in the non-recrystallization region, quenched and tempered at a heating rate of 20°C/s. A relatively large film of cementite was distributed mostly at the lath boundaries in both (a) (the steel not subjected to ausforming) and (b) (the steel tempered at the slow heating rate of 0.3°C/s after ausforming). Cementite, meanwhile, was observed within the laths as well as at the lath boundaries, and spheroidal and fine cementite

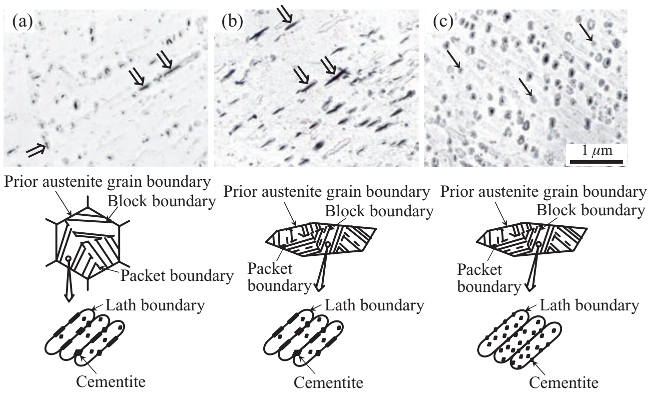

Fig. 3 Uniform dispersion of fine cementite of HYD1100LE steel by ausforming and rapid heating and tempering: rolled in (a) Recrystallization temperature region and (b), (c) non-recrystallization temperature region of austenite; Heating rate of (a), (b) is 0.3°C/s and that of (c) is 20°C/s (⇒: Lath boundary, →: Within lath)

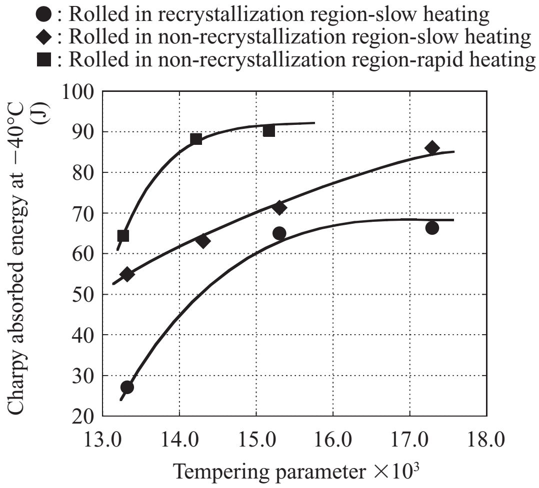

Fig. 4 Improvement of low temperature toughness by ausforming and rapid heating and tempering of HYD1 100LE steel

was uniformly distributed in (c) (the steel tempered at the rapid heating rate of 20°C/s after ausforming).

The site of cementite nucleation was reported to change from the lath boundaries to within the laths in the heating process during tempering[13,15,16]. The dislocation density is greatly increased after quenching, especially in the steels subjected to ausforming[5,6]. In addition, because of the rapid heating rate, the delay in the dislocation recovery of the rapidly heated material is greater than that of the slowly heated material under the same temperature conditions during heating. Thus, the dislocation density of (c) (the steel tempered at a rapid heating rate after ausforming) is the highest among (a), (b) and (c) when it reaches the temperature at which the site of selective cementite nucleation changes from the lath boundaries to within the laths, causing the nucleation of cementite from dislocation within the laths. The most uniform dispersion of the finest cementite of (c) would be attributed to this cementite nucleation within the laths.

2.4 Improvement of Low Temperature Toughness and Delayed Fracture Resistance by Fine Microstructure and Uniform Dispersion of Fine Cementite

Figure 4 shows the effect of the fine microstructure (section 2.2) and cementite refinement (section 2.3) on the low temperature toughness of the YP1100 MPa class steel. The horizontal axis of Fig. 4 is a tempering parameter (T.P.) calculated to include both the heating and cooling processes[19].

The low temperature toughness of the ausformed material was superior to that of the non-ausformed material and the toughness of the rapidly heated and tempered material was superior to that of the slowly heated and tempered material. Thus, the ausformed and rapidly heated material with the fine microstructure and refined cementite showed the most excellent low temperature toughness.

Figure 5 shows the effect of cementite dispersion on the delayed fracture resistance of YP960 and YP1100 MPa class ausformed steels. Cementite dispersion was adjusted to different levels by changing the heating rate during tempering. Round tensile test specimens were charged with hydrogen cathodically to realize a diffusible hydrogen content of 0.38–0.75 mass ppm. The specimens were plated with zinc immediately after the hydrogen charging to avoid hydrogen evolution and then subjected to a slow strain rate test (SSRT)[2]. Delayed fracture resistance performance was evaluated by the safety index of the delayed fracture resistance illustrated in the following Eq. (1).

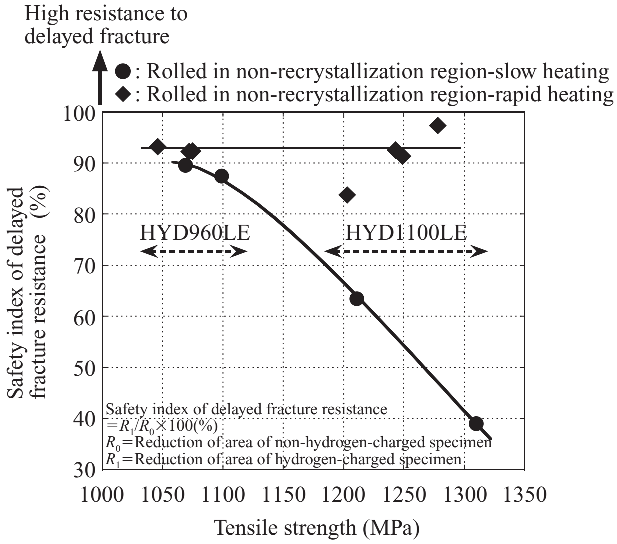

Fig. 5 Improvement of resistance to delayed fracture by rapid heating and tempering

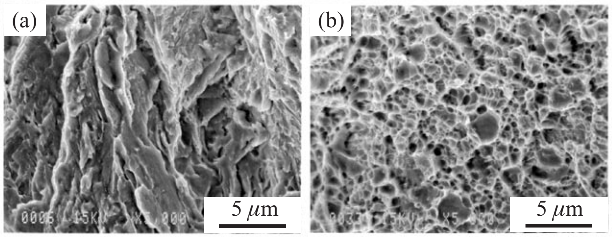

Photo 1 Suppression of hydrogen induced quasi-cleavage fracture by uniform dispersion of fine cementite of HYD1100LE steel: (a), (b) SEM images of fracture appearance of hydrogen-charged specimen; (a) Ausforming and slow heating (TS = 1 310 MPa); (b) Ausforming and rapid heating (TS = 1 278 MPa)

$$R_1/R_0 \times 100\ (\%) \quad (1)$$

Where R_0 and R_1 represent the reductions of area of the specimen without hydrogen charging and the specimen with hydrogen charging, respectively.

As illustrated in Fig. 5, the material subjected to the slow heating and tempering exhibited a decreasing safety index of the delayed fracture resistance as the tensile strength rose. In contrast, the material subjected to the rapid heating and tempering showed no deterioration in the safety index of the delayed fracture resistance even at the tensile strength of 1 300 MPa class. This indicated the high resistance to delayed fracture of the rapidly heated and tempered material with refined cementite.

Photo 1 shows SEM images of fracture appearances after SSRT of the hydrogen-charged materials subjected to the slow heating and the rapid heating, respectively. Both of them had a tensile strength of about 1 300 MPa. The slowly heated and tempered material showed a quasi-cleavage fracture near the fracture origin at the outer edge of the fracture appearance. On the other hand, the appearance of the fracture of the rapidly heated and tempered material was dominated by a dimple fracture mode.

Judging from this observation of the fracture appearances, the high resistance to delayed fracture of the rapidly heated and tempered material may be attributed to the change of the fracture mode from quasi-cleavage fracture to ductile fracture via the suppression of the quasi-cleavage fracture through the cementite refinement.

3. Mechanical Properties of the Developed Steels

3.1 Chemical Composition and Manufacturing Process of the Developed Steels

Two types of ultra high strength steel plate for construction and industrial machinery application (JFE-HYD960LE and JFE-HYD1100LE) were manufactured at a plate mill. The newly developed technologies mentioned in section 2 were applied to the manufacture and the mechanical properties of the base plates and welded joint were evaluated.

Table 2 Chemical compositions of the developed steels

(mass%)

Grade	C	Si	Mn	P	S	Others	C_{eq} (%)
HYD960LE	0.13	0.37	1.5	0.010	0.002	Cr, Mo, Nb, B, etc.	0.57
HYD1100LE	0.17	0.41	1.1	0.007	0.001	Cr, Mo, Nb, B, etc.	0.59

Table 2 shows an example of the chemical composition of the developed steels. The plate thickness for manufacturing ranged from 12.0 mm to 32.0 mm. The steel plates were manufactured by a controlled rolling-direct quenching-HOP (CR-DQ-HOP) process. With this process, the steel plates were quenched directly after controlled rolling and then tempered at a rapid heating rate on the same production line as the rolling and quenching processes. Ausforming and rapid heating and tempering via direct quenching and HOP decreased the carbon content and carbon equivalent to the fullest extent. The low carbon content and low carbon equivalent design thus realized led to excellent weldability. The carbon content and carbon equivalent of YP960 MPa class steel are 0.13 mass% and 0.57% and those of YP1100 MPa class steel are 0.17 mass% and 0.59%, respectively.

3.2 Mechanical Properties of Base Plates

Table 3 shows an example of the mechanical properties of the base plates of the developed steels. Both the tensile properties and Charpy impact properties sufficiently satisfied the targeted properties. Excellent low temperature toughness, one of the features of the developed steels, was also confirmed.

Figure 6 shows an example of hardness distribution and microstructure etched by nital through the thickness

Table 3 Mechanical properties of base plates of the developed steels (t: 32 mm)

Grade	Tensile properties			Charpy impact properties	Remarks
	YS* (MPa)	TS** (MPa)	El*** (%)	$_vE_{-40^\circ C}$**** (J)	
HYD960LE	1 061	1 123	31	191	Developed steel (DQ*****-HOP ******)
HYD1100LE	1 173	1 277	23	61	

*Yield strength **Tensile strength ***Elongation
****Absorbed energy at −40°C
*****DQ: Direct quenching
******HOP: Heat-treatment On-line Process

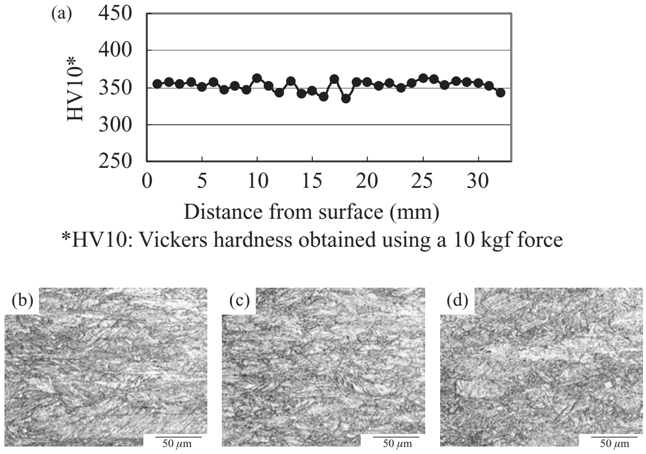

Fig. 6 Hardness distribution (a) and optical micrographs (b), (c), (d) through plate thickness of HYD960LE steel (thickness = 32 mm): (b), (c), (d) nital etching; (b) 1 mm from surface; (c) quarter part of plate thickness; (d) middle part of plate thickness

of the HYD960LE steel. The HYD960LE steel exhibited an ausformed lath martensite microstructure in which the prior austenite grain expanded from the surface to the middle part of the plate thickness, with a uniform hardness distribution through the thickness.

3.3 Mechanical Properties of Welded Joint

Table 4 shows welding procedure and welding conditions of the HYD960LE steel and **Table 5** shows the mechanical properties of the welded joint. Both the tensile properties and Charpy impact properties completely satisfied the targeted properties. This newly developed steel also had excellent heat-affected zone (HAZ) toughness due to the low carbon content and low carbon equivalent design.

4. Conclusion

With the development of JFE-HYD960LE and JFE-HYD1100LE, JFE Steel has expanded its production lineup of steel plates for application to construction and industrial machinery. These newly developed steels show excellent low temperature toughness, high resistance to delayed fracture and excellent weldability through the application of ausforming technology and rapid heating and tempering technology. Construction and industrial machinery has expanded in scale in recent years. In light of this, we expect the market demand for the steel plates of these types to expand at an accelerating pace.

Table 4 Welding procedure and welding conditions of HYD960LE steel

Plate thickness	32 mm
Groove configuration	X-Groove
Welding method	GMAW (90%Ar-10%CO_2)
Welding consumables	Bohler Thyssen Union X96 solid wire-1.2 mmϕ
Heat input	17.3 kJ/cm
Preheat temperature	150°C
Interpass temperature	125–175°C

Table 5 Mechanical properties of welded joint of HYD960LE steel (*t*: 32 mm)

Grade	Tensile properties		Charpy impact properties	
	TS* (MPa)	Fractured position	Location	$_{v}E_{-40°C}$** (J)
HYD960LE	1057 1059	WM*** WM***	WM***	50
			FL****	50
			HAZ*****	180

*Tensile strength **Absorbed energy at −40°C
***WM: Weld metal ***FL: Fusion line
****HAZ: Heat affected zone

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