Development of Manufacturing Technologies of High Performance Longitudinally Profiled Steel Plates†

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Abstract:

Applied stress to structural materials often varies in longitudinal directions. LP plates, which stand for longitudinally profiled steel plates, are plates whose thickness varies continuously along the length within a plate. They are used for shipbuilding and bridges in order to correspond to change of the stresses without joining of plates of different thicknesses, and enable cost savings by reducing steel weights and welded joints. In this paper, various special technologies for LP plates are shown, for example, rolling, accelerated cooling and shearing. By developing such technologies, manufacturing of LP plates became substantially automated to perform mass production. And the production of LP plates is increasing year by year.

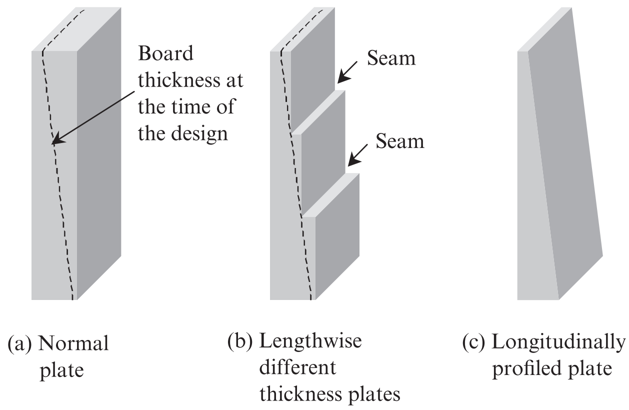

Fig. 1 Example of an omission of seams and reduction of weight by using LP plate

1. Introduction

In ships and other large-scale structures, the plate thickness is generally thicker in the lower part of the structure and becomes progressively thinner in the upper part. As problems in this type of structure, (1) In order to reduce the weight of the steel materials used and achieve weight reduction, joints between a large number of plates of different thicknesses, for example, by welding, are necessary, and (2) welding or other joining work increases with the use of plates of many thicknesses for weight reduction. As a means of solving these problems, if it is possible to use a plate in which the plate thickness is changed in the longitudinal direction, a structure with the minimum necessary weight can be realized without welding or other joining (**Fig. 1**). Therefore, in response to the increasing needs for energy saving and reduction of CO_2 emissions in marine transportation, etc. and for cost reduction in all industries, beginning with shipbuilding, supply of longitudinally profiled (LP) steel plates that enable weight reduction and reduce welding or other joining work in steel structures had been strongly desired. However, many issues related to manufacturing technologies and productivity must be overcome for the industrial mass production of LP steel plates. These include (1) Special rolling technology which is necessary, in which the thickness are to be changed in the longitudinal direction during hot rolling, and it is difficult to secure the thickness accuracy and flatness; (2) the difference in plate thickness in the longitudinal direction causes non-uniform mechanical properties when properties are built into the product by cooling; (3) it is necessary to locate the product cutting position by removing the steel plate from the product shearing line and performing off-line manual measure-

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ments of the plate thickness in the longitudinal direction, etc. As a result, an industrial mass production technology for LP steel plates had not been established. Therefore, JFE Steel developed a variety of technologies to overcome the above-mentioned issues, and established a system that enables industrial mass production of high accuracy, high quality LP steel plates with diverse thickness profiles.

2. Examples of Applications of LP Steel Plates

Figure 2 shows the thickness profiles of LP steel plates which can be manufactured by JFE Steel. Available plate dimensions are controlled in units of 0.01 mm in the thickness direction and 1 mm in the plate width and length directions, supporting many types of profiles corresponding to changes in the designed plate thickness. Dimensional accuracy conforms to the same standard tolerances as in flat plates. Materials with tensile strength of from 400 N/mm^2 class up to 570 N/mm^2 class are available. Uniform strength distribution over the full plate length was realized. It is possible to produce LP steel plates of almost all steel types for shipbuilding and bridges. JFE Steel has developed technologies for producing LP steel plates with the diverse profiles shown in Fig. 2 with high accuracy, high quality, and high efficiency, enabling stable supply of more than 10 000 tons per month.

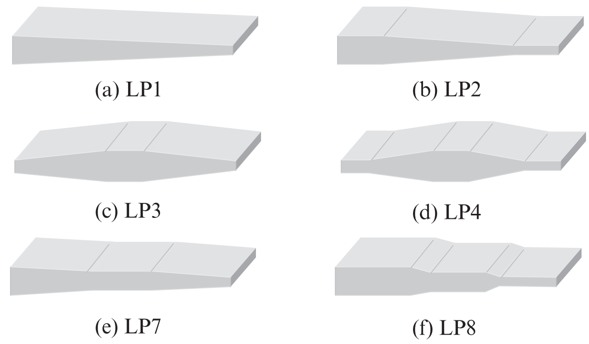


Fig. 2 Various thickness profiles of LP plates

2.1 Effects of Application of LP Steel Plates in Shipbuilding Field[1–3]

Figure 3 shows examples of typical applications of LP steel plates in shipbuilding. For example, in the transbulkhead, it is necessary to reduce the plate thickness from the ship bottom to the top. Conventionally, a large number of plates of different thicknesses were joined by welding so as to reduce the plate thickness as stress decreased with the aim of achieving weight reduction. Use of an LP steel plate in this part enables a further reduction in the weight of the steel materials as well as a reduction in the number of plate joints. In addition to the transbulkhead, LP steel plates are used in many other parts, including the upper deck, bottom plates, etc. In one actual case, approximately 2 500 tons of LP steel plates were used in a 170 000 ton class bulk carrier, thereby achieving a 700 m reduction in weld length and a 218 tons reduction in the weight of steel materials used. To date, LP steel plates have been applied in more than 250 ships.

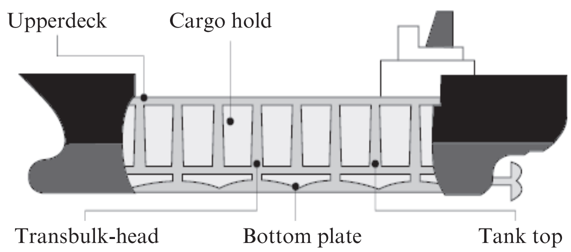


Fig. 3 Examples of typical application LP plate for ship-building

2.2 Effect of Application of LP Steel Plates in Bridge Field[4)]

As an example of needs in the bridge field, bridge girder flanges are discussed in the following. In bridge girder flanges, the necessary stress changes in the longitudinal direction. Accordingly, in bolted joints of steel materials with different plate thicknesses corresponding to the necessary stress, it is necessary to use a filler plate to compensate for the plate thickness difference in the joint between the members, as illustrated in **Fig 4** (a). As shown in Fig. 4 (b), use of LP steel plates makes it possible to reduce the number of joints and omit the filler plates in bolted joints. Application of LP steel plates in this manner also results in a structure with a more attractive appearance. Up to the present, LP steel plates have been used in more than 10 bridges.

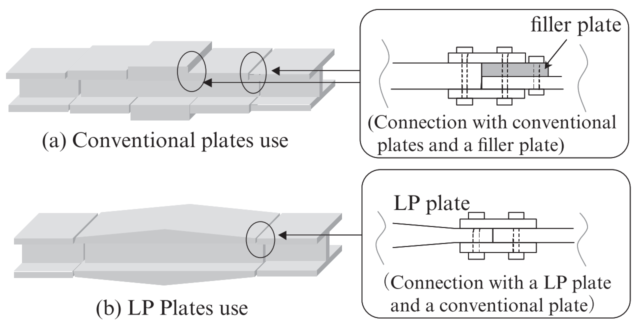


Fig. 4 Example of typical application LP plate for bridge figure flange

3. LP Steel Plate Manufacturing Technologies

Figure 5 shows an outline of the LP steel plate manufacturing process. In manufacturing plates, a slab is reheated to approximately 1 150°C in a reheating furnace, and its thickness is then reduced by passing the

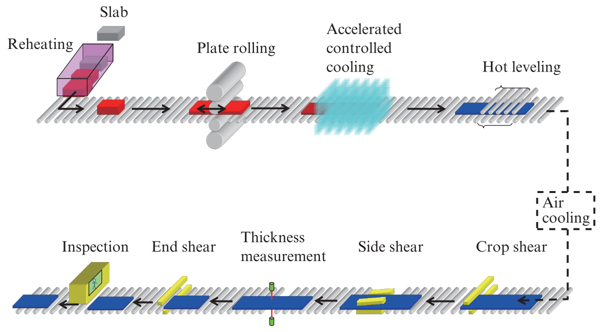


Fig. 5 Manufacturing process for LP plate

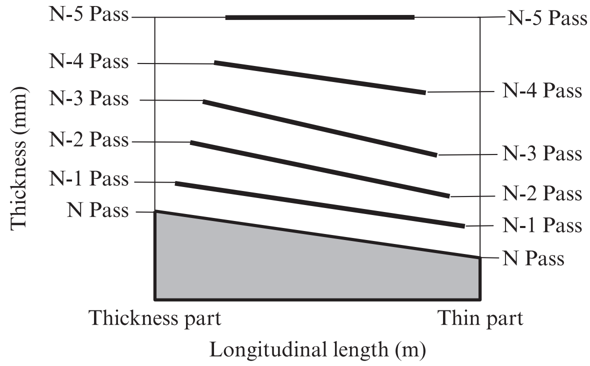


Fig. 6 Example of a rolling pass schedule for LP plate

plate through the gap between the top and bottom rolls of the plate mill. Plates are normally rolled to the prescribed thickness by reversing rolling (i.e., repeatedly passing the plate back and forth through a single mill) while progressively reducing the gap between the top and bottom rolls in a stepwise manner, and generally requires more than ten rolling passes. The action of passing a plate through the roll gap is called a "pass," and the amount of reduction of the plate thickness in each pass is called "rolling reduction." The process in which the number of passes and the rolling reduction in each pass from the slab thickness to the product thickness are decided is called the "rolling pass schedule." In the case of normal thickness products (i.e., flat plates), the same thickness is obtained over the entire length by controlling the mill so that the gap between the top and bottom rolls does not change during a rolling pass. After plate rolling, controlled cooling by water cooling is performed to obtain the required strength and toughness, hot leveling is performed to secure flatness, and the plate is then sent to the product shearing line. At the shearing line, product plates of the specified width and length are cut from the as-rolled plate.

Based on the plate manufacturing process described above, technical development was carried out in each of the processes of plate rolling, controlled cooling, hot leveling, and shearing to enable the manufacture of LP steel plates. The respective developed technologies are described in the following.

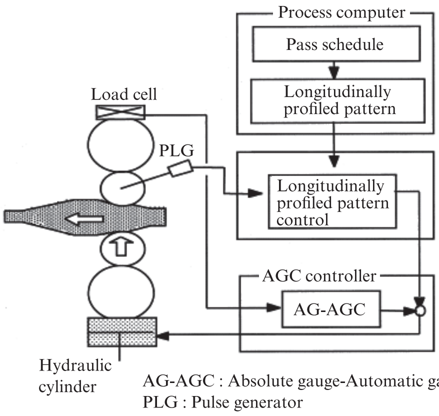
3.1 Development of Rolling Pass Schedule Calculation for LP Steel Plates

In the plate rolling mill, the top and bottom rolling rolls are rotated by motors, and plates are passed through the gap between these rolls. The amount of thickness reduction, that is, the rolling reduction which is possible in one pass, is limited by the power of the motors that drive the rolling rolls and the mechanical strength of the mill. During rolling, bending of the rolls in the transverse direction occurs due to rolling reaction force, causing thickness differences in the plate width direction. If the width-direction thickness difference at the entry side of the rolling pass and the plate thickness difference after rolling change greatly, the longitudinal elongation at the center and edges of the plate transverse direction will also differ, and if this difference exceeds the allowable range, plate buckling will occur and flatness will be disturbed. From the viewpoint of efficiency, it is necessary to set the rolling reduction in each pass of the rolling pass schedule to the maximum possible reduction, given the above-mentioned limitations of mill motor power and the mechanical strength of the mill, so as to enable rolling to the product thickness in the minimum number of passes, while also determining the rolling reduction in each pass in such a way that flatness is maintained.

Unlike flat plate rolling, when rolling LP steel plates, the plate thickness is changed greatly within each pass, and as a result, the rolling reduction changes within each pass. Due to the above-mentioned limitations of mill motor power and mill mechanical strength and need to secure plate flatness, it is not possible to give the required plate thickness difference to the product in one pass. Therefore, when calculating the rolling pass schedule for LP steel plates, first, the rolling pass schedule is prepared by the same logic as in the case of ordinary materials (flat plates), targeting the thickness of the thinnest part. Next, the rolling pass schedule of the thickest part is calculated. However, because the plate thickness of the thickest and thinnest parts is the same at the start of rolling, and the number of rolling passes is also the same, the rolling reduction of the thickest part must be smaller than the rolling reduction of the thinnest part in each pass. Therefore, the reduction of the thickest part in each pass is determined while decreasing the reduction of the thinnest part, considering flatness, variations in transverse thickness in the plate, and the possible speed of roll gap changes during a pass, based on the rolling reduction of the thinnest part in each pass. **Figure 6** shows an example of the rolling pass schedule for an LP steel plate.

3.2 Gauge Profile Control of LP Steel Plates[5,6)]

Figure 7 shows the outline of the gauge control system for LP steel plates. The system comprises a process computer, which calculates the rolling pass schedule and decides the longitudinal thickness profile (change of thickness in the longitudinal direction) to be given in each pass, etc.; the reduction direct digital controllers (DDC), which determines the change in the roll gap for giving the target longitudinal thickness profile while tracking the position in the longitudinal direction; and automatic gauge control (AGC), which changes the roll gap during a pass by controlling the position of the hydraulic cylinders. During rolling, a pressing force (rolling reaction force) of several thousand tons acts on the rolling rolls, causing the rolls to deform, and at the same time, the roll gap expands by an order of several millimeters in comparison with that before rolling because the mechanical parts of the plate mill which supports the rolls also deforms elastically. For this reason, the roll gap before rolling is set on the narrow side by predicting the change in the roll gap due to rolling reaction force. In passes that produce the longitudinal thickness profile, the roll gap is changed by the hydraulic AGC cylinders, aiming at the thickness profile decided by the process computer, but accompanying this, the rolling reaction force also changes, and the roll gap changes by a corresponding amount. Since the roll gap also varies due to fluctuations in the rolling reaction force due to temperature differences in the plate, etc., the longitudinal profile cannot be given as targeted. Therefore, the changes in the roll gap caused by deformation of the rolls and the rolling mill due to the difference between the actual rolling reaction force and the reaction force predicted before rolling are calculated in real time, and roll gap changes are corrected by the hydraulic AGC cylinders. In other words, it is possible to obtain the targeted longitudinal thickness profile by constantly compensating for changes in the roll gap caused by external disturbances other than the amount of roll gap change required by the longitudinal thickness profile which is to be given to the plate.



AG-AGC : Absolute gauge-Automatic gauge control
PLG : Pulse generator

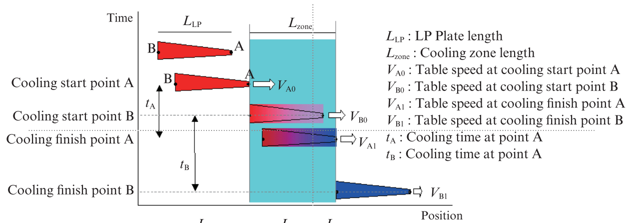
Fig. 7 Automatic gauge control system configuration for LP plate

3.3 Controlled Cooling of LP Steel Plates

As with conventional materials, controlled rolling and controlled cooling, that is, the thermo-mechanical control process (TMCP), may be applied in the manufacture of LP steel plates with tensile strengths of 490 N/mm^2 and higher in some cases in consideration of weldability. When applying controlled cooling, if water cooling is performed in the same manner as with flat plates, deviations in the quality (mechanical properties) of the plate will occur as a result of the difference in the cooling stop temperatures of the thick part and the thin part caused by the difference in the cooling rate due to the different plate thicknesses. In order to prevent this, JFE Steel developed a controlled cooling method which produces difference in cooling time continuously in the longitudinal direction by appropriate control of the plate transfer speed and acceleration/deceleration rates during cooling. That is, the cooling time of thick part is extended by slowing the transfer speed in the cooling zone as the plate thickness increases. **Figure 8** shows an outline of the accelerated controlled cooling system for LP steel plates. The plate is passed through the cooling zone at the proper transfer speed to satisfy the necessary cooling time, which is decided respectively each cooling start temperature and target cooling stop temperature for the thick part and the thin part.

3.4 Hot Leveling for LP Steel Plates

Hot leveling of LP steel plates is performed while changing the gap between the top and bottom leveling rolls, following the plate profile. Basically, a control technology was developed so as to obtain a uniform leveling effect over the full length of the plate by controlling the leveling roll gap while tracking the longitudinal position, based on the longitudinal thickness profile measured after the completion of hot rolling. This technology is similar to control of the longitudinal thickness profile in each pass in hot rolling.



$$t_A = \frac{L_{LP}}{\frac{1}{2}(V_{A0}+V_{B0})} + \frac{L_{ZONE}-L_{LP}}{\frac{1}{2}(V_{B0}+V_{A1})}$$

$$t_B = \frac{L_{ZONE}-L_{LP}}{\frac{1}{2}(V_{B0}+V_{A1})} + \frac{L_{LP}}{\frac{1}{2}(V_{A1}+V_{B1})}$$

Fig. 8 Accelerated controlled cooling system for LP plate

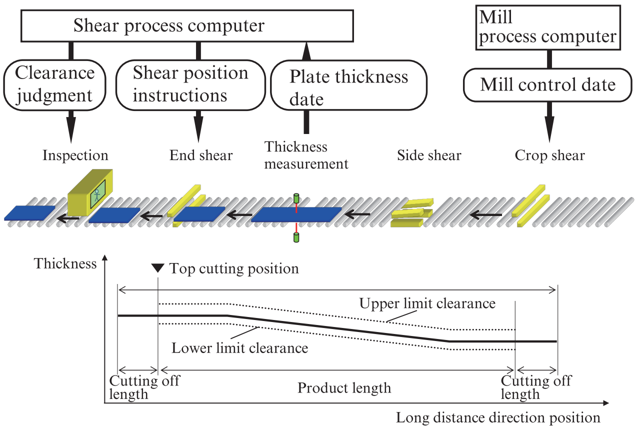


Fig. 9 Summary of the automatic measuring system using the thickness measurement for LP plate

3.5 Automatic Product Cutting Position Detection for LP Steel Plates

Because LP steel plates have a thickness slope in the longitudinal direction, products must be cut from the proper position in the as-rolled plate in order to secure the specified thickness. For example, in an LP steel plate with a thickness slope of 4/1 000, if the product cutting position deviates from the correct position by 100 mm, a 0.4 mm deviation in plate thickness will occur, and in this case, the product will not satisfy the plate thickness tolerance. Therefore, JFE Steel developed a system for determining the optimum product cutting position based on plate thickness values measured by a thickness gauge installed in the product shearing line. **Figure 9** shows an outline of the automatic measuring system using the plate thickness gauge.

4. Production Record of LP Steel Plates

4.1 Actual Thickness of LP Steel Plates

JFE Steel carried out development of a wide range of technologies related to the manufacture of LP steel plates, and established a system which enables high efficiency production of high accuracy, high quality LP steel plates that satisfy diverse customer requirements. **Figure 10** shows typical examples of the actual thickness (values measured by thickness gauge at product shearing line) of LP steel plates produced by JFE Steel. Figure 10 (a) shows an example of an LP steel plate for ship transbulkheads; this is a unidirectional slope product with a thickness difference of 3.5 mm. The results in Fig. 10 (b) and (c) are both for products for bridge flanges. Figure 10 (b) shows a unidirectional slope product with flat plate sections at the two ends. It has a thickness difference of 30 mm and a slope of 3/1 000; the length of the thick flat plate section is 2.4 m, and the length of the thin flat plate section is 4.0 m. Fig. 10 (d) is a unidirectional slope LP steel plate in which the plate thickness is changed in two steps and is applied in the shipbuilding field.

4.2 Actual Material Properties of LP Steel Plates

Figure 11 (a) and (b) show the actual results of a tensile test and Charpy impact test of a TMCP type yield point of 460 MPa class unidirectional slope LP steel plate. Values that satisfy the standard values for both strength and toughness were obtained at the Top (t: 60 mm), Mid. (t: 55 mm), and Bot. (t: 50 mm) positions, which have different plate thicknesses.

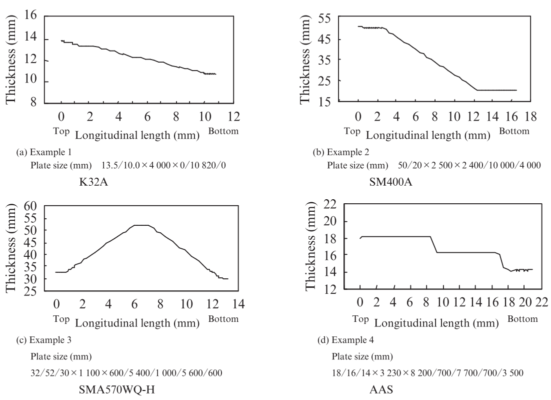
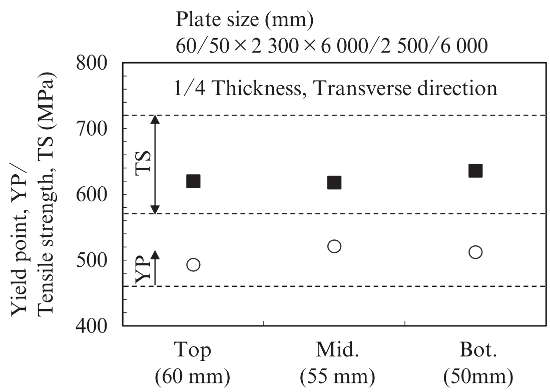
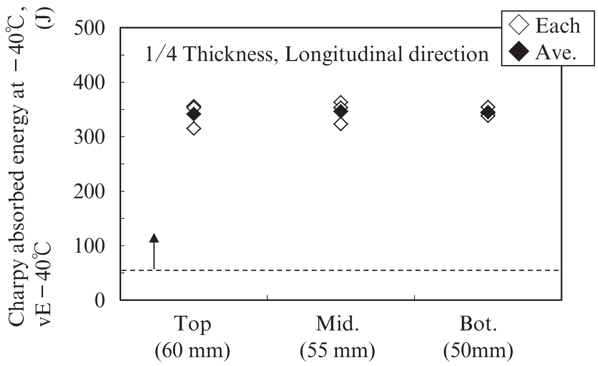


Fig. 10 Examples of longitudinal profiles of actual thickness



(a) Result of tensile test for LP plate (460 MPa Class)



(b) Result of Charpy impact test for LP plate

Fig. 11 Result of materials test for LP plate

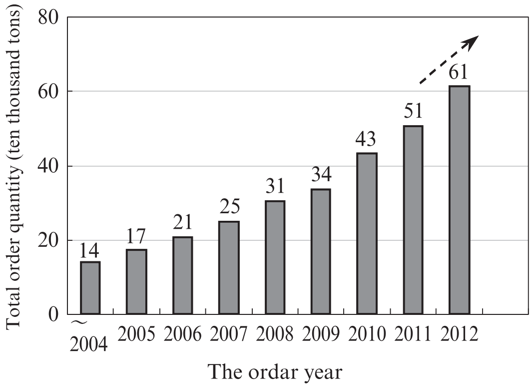


Fig. 12 Supply record of LP plates

LP steel plates have the distinctive feature that the plate thickness changes in the longitudinal direction. Consequently, however, ingenuity is necessary when properties are built into the product in TMCP. JFE Steel optimized the chemical composition design and manufacturing condition setting, beginning with the development of a controlled cooling process utilizing the *Super*-OLAC™, and realized uniformity of mechanical properties in the longitudinal direction.

4.3 Supply Record of LP Steel Plates

Since LP steel plates were first applied as steel plates for shipbuilding in 1993, their record of use has steadily increased. As mentioned in Chapter 2, LP steel plates have been used in more than 250 ships and in more than 10 bridges. **Figure 12** shows the cumulative supply record of LP steel plates. As of 2012, cumulative orders had reached 600 000 tons.

5. Conclusion

Examples of applications of LP steel plates by customers were presented, and JFE Steel's LP steel plate manufacturing technologies and production results were introduced.

(1) LP steel plates are steel plates in which the plate thickness is changed in the longitudinal direction. When used as steel materials for shipbuilding and bridges, LP steel plates contribute to reduction of structural weight and omission of joining processes.

(2) The following technologies were developed, and a technology for stable mass production of LP steel plates with diverse profiles was established. Monthly production capacity is more than 10 000 tons.
   (a) Technology for imparting accurate plate thickness change in the longitudinal direction by high accuracy control of the roll gap in hot rolling.
   (b) Technology for securing uniform material properties when properties are built into the product by water cooling, irrespective of longitudinal differences in plate thickness.
   (c) Technology for uniform leveling in the longitudinal direction by high accuracy control of the leveling roll gap in hot leveling.
   (d) Product cutting technology enabling automatic location of the product cutting position on the production shearing line.

(3) Since LP steel plates were first applied as steel plates for shipbuilding in 1993, their record of use has steadily increased, and orders had reached a cumulative total of 600 000 tons as of 2012.

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