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New Products & Technologies

TS 100-kgf/mm^2-Class Heavy Section Plate*

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1 Introduction

At present, HT 80-kgf/mm^2 steel plates are, as is well known, used for penstocks, bridges, offshore structures, and spherical tanks. Recently, rapid increases in the size of welded structures have been encouraged by the development of high-strength heavy section steel plate with excellent toughness and weldability. As the trend toward heavier section steel plates has continued, not only 80-kgf/mm^2 class but even 100-kgf/mm^2 class plate has been called for, with the aim of reducing structure weight. Examination of HT 100-kgf/mm^2 steel began as early as 1970, and to certain degree performance was verified, but concrete measures for its manufacture were not realized at the time. With recent progress in steelmaking techniques, however, the stable manufacture of high-quality steel plate has become possible, and the practical use of 100-kgf/mm^2 steel has come under concrete study. Against this background, Kawasaki Steel Corp. developed manufacturing techniques for 100-mm-thick HT 100-kgf/mm^2 steel plate[1,2] which possesses the same level of weld crack resistance, and demonstrates satisfactory performance under the same use conditions, as HT 80 kgf/mm^2. The characteristics of this material, including its base metal, welded joint, and rupture characteristics, are described below.

2 Manufacturing Techniques

The authors examined the development of 100-mm-thick HT 100-kgf/mm^2 steel plate from both the composition viewpoint and that of manufacturing method, within the composition range $C \leqq 0.14\%$, $Si \leqq 0.25\%$, $Mn \leqq 1.0\%$ and $Ni \leqq 3.0\%$, taking into consideration that the steel must have the same base-metal characteristics at the same carbon equivalent ($C_{eq.} \leqq 0.60\%$) as HT 80-kgf/mm^2-class heavy section steel and that large-heat-input narrow-gap welding with a welding heat input of 60 kJ/cm must be applicable.

To manufacture a high-strength steel plate having the same composition as HT 80-kgf/mm^2 steel, a means of lowering the tempering temperature is generally adopted to maintain sufficient strength. On the other hand, lowering the tempering temperature is detrimental to toughness, particularly in the surface layer, indicating that the tempering temperature alone is not a sufficient condition for the manufacture of high-quality steel plates with satisfactory strength and toughness throughout the thickness of the plate.

In the surface layer, a coarse martensite single-phase structure forms, reducing toughness. It has generally been believed that toughness after tempering is greatest if the structure after quenching is a mixed one of martensite and lower-part bainite. In the present study, an examination was made to determine what composition system and alloy addition quantities would result in this type of mixed structure across the plate thickness. It was found that surface layer toughness can be improved without greatly changing the structure and strength of the plate in the thickness direction by adding a proper amount of Ni and lowering Mn and Si, measures which reduce the cooling-rate dependence of structural changes. The upper limit of Ni addition was set at 3% for economic reasons, and the lower limit of Mn addition was set at 0.8% in view of the balance between the loss of strength and improved toughness. The effect of lowered Si content in improving toughness is considered attributable to the facts that the hardenability of the steel plate was somewhat lowered by the reduction in Si content and that the austenite structure of the same grain size sub-divided into smaller martensite structure, as shown in **Photo 1**. A decrease in Si is also expected to decrease the quantity of island-shaped martensite at the weld. Thus, for both the mother plate and the weld, lower Si content is a desirable composition

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(a) Low Si steel (0.11% Si) (b) Ordinary Si steel (0.25% Si)

Photo 1 Effect of Si content on martensite structure

system for maintaining toughness.[3)]

Further, in heavy section steel plate, high welding efficiency assumes greater importance. Therefore, in narrow-gap large heat input SAW at heat inputs of 45 kJ/cm and above, an examination was made of composition systems in which softening of the weld HAZ is small. It was found that an addition of V is effective in preventing softening of the HAZ without a loss of HAZ toughness, and thus the addition of a proper amount of V was required in the present steel. On the other hand, a quenching method in which the quenching temperature is lowered within the range where the strength of the plate center portion can be maintained has been used as a plate manufacturing technique to control coarsening of of the austenite particles in the surface layer and secure toughness.

3 Welding Materials

Welding materials were developed for use with HT 100-kgf/mm^2 steel in submerged arc welding (SAW), shielded metal arc welding (SMAW), and MIG and TIG welding. All these welding materials offer excellent low temperature crack resistance, high toughness, and satisfactory usability.

(1) In SAW welding materials, the basicity of the flux was designed to be on the high side, and the diffusible hydrogen and oxygen quantities in the weld metal were reduced. By adding a proper amount of carbonate, ultra-low oxygen content was achieved, thereby improving the low temperature crack resistance of the weld. Toughness was improved by controlling the oxygen content of the weld metal. Satisfactory usability was ensured by adjusting the MgO-CaF_2 slag composition to increase the contraction of the slag as a measure for promoting slag spalling during narrow-gap welding.

(2) With the SMAW welding material, ultra-low hydrogen content was achieved by reducing the hydrogen source in the shielding material and by use of a non-hygroscopic binder in the coating as a measure against moisture absorption, thereby improving low temperature crack resistance.

4 Characteristics of Newly Developed Steel

The base metal characteristics, formability, and weldability of the 100-mm-thick HT 100-kgf/mm^2 steel plate are shown in **Table 1**; characteristics of SAW and SMAW welded joints are shown in **Table 2** and **3** respectively.

4.1 Base Metal Performance

The composition design involved lowered Si content and proper additions of Ni, Mn, and B; the manufacturing process included re-heating, quenching, and tempering. As shown in Table 1, the chemical composition of the steel plate is a 0.08%Si-0.84%Mn-2.67%Ni-0.0012%B system, and the $C_{eq.}$ is the same as HT 80-kgf/mm^2-class heavy section steel plate.

Microstructures at various plate-thickness positions of the base metal, shown in **Photo 2**, are mixed structures of martensite and lower bainite, and their mechanical properties fully satisfy the target performance.

Figure 1 shows the measured results of hardness of the base metal in the plate-thickness direction. Both the top and bottom surfaces have an hardness of about HV 330, while the center is about HV 320. Although the material is heavy section plate, its mechanical properties show little variation, indicating that the product is high-quality steel plate of excellent uniformity.

4.2 Formability

Charpy impact characteristics after pre-strain aging treatment show virtually no change at a strain quantity of 3%. When the strain quantity is increased to 5%, toughness drops slightly. However, $_vT_S$ is -72°C at 1/4 thickness and -97°C at 1/2 thickness, thus maintaining high toughness of -60°C or below and indicating that the steel has sufficient formability.

Table 1 Characteristics of 100-mm-thick HT100 kgf/mm^2 steel plate

<table>
<tr><td rowspan="13">Base metal performance</td><td rowspan="2">Chemical comp. (%)</td><td>C</td><td>Si</td><td>Mn</td><td>P</td><td>S</td><td>Cu</td><td>Ni</td><td>Cr</td><td>Mo</td><td>V</td><td>Al</td><td>B</td><td>N</td><td>$C_{eq.}$</td><td>P_{cm}</td></tr>
<tr><td>0.13</td><td>0.08</td><td>0.84</td><td>0.001</td><td>0.001</td><td>0.24</td><td>2.67</td><td>0.47</td><td>0.48</td><td>0.059</td><td>0.067</td><td>0.0012</td><td>0.0021</td><td>0.558</td><td>0.299</td></tr>
<tr><td rowspan="2">Structure</td><td colspan="5">Microstructure</td><td colspan="5">Cleanliness</td><td colspan="5">Austenite grain size</td></tr>
<tr><td colspan="5">Martensite & bainite</td><td>1/4 t</td><td colspan="4">dA = 0%, dB = 0%
dC = 0.01%</td><td colspan="5">About No.7</td></tr>
<tr><td>Hardness</td><td colspan="15">Top & Bottom surface HV = 330, 1/2 t: HV = 320</td></tr>
<tr><td rowspan="6">Mechanical properties</td><td colspan="3" rowspan="2"></td><td colspan="5">Tensile test</td><td colspan="5">Charpy impact test</td><td colspan="2">Bend test</td></tr>
<tr><td colspan="2">YS≧90*1 (kgf/mm^2)</td><td colspan="2">TS = 97~115*1 (kgf/mm^2)</td><td>El (%)</td><td colspan="2">vE_{-60}≧4.8*1 (kgf·m)</td><td colspan="2">vT_S≦−60*1 (°C)</td><td>vT_E (°C)</td><td colspan="2">Radius R = 2t</td></tr>
<tr><td rowspan="2">L</td><td colspan="2">1/4 t</td><td colspan="2">94.4</td><td colspan="2">98.6</td><td>23</td><td colspan="2">22.4</td><td colspan="2">−88</td><td>−88</td><td colspan="2" rowspan="2">Good</td></tr>
<tr><td colspan="2">1/2 t</td><td colspan="2">95.8</td><td colspan="2">98.7</td><td>24</td><td colspan="2">23.2</td><td colspan="2">−102</td><td>−101</td></tr>
<tr><td rowspan="2">T</td><td colspan="2">1/4 t</td><td colspan="2">94.8</td><td colspan="2">98.4</td><td>22</td><td colspan="2">23.7</td><td colspan="2">−86</td><td>−86</td><td colspan="2" rowspan="2">Good</td></tr>
<tr><td colspan="2">1/2 t</td><td colspan="2">95.8</td><td colspan="2">98.6</td><td>22</td><td colspan="2">22.8</td><td colspan="2">−111</td><td>−109</td></tr>
<tr><td rowspan="2">Toughness</td><td colspan="5">CTOD</td><td colspan="6">Deep notch</td><td colspan="4">ESSO</td></tr>
<tr><td colspan="5">0.764mm
0.731mm (at 0°C)</td><td colspan="6">σ_{net} = 102.5 kgf/mm^2
K_C = 1048.4 kgf/mm$^{3/2}$ (at −60°C)</td><td colspan="4">K_{ca} = 812 kgf/mm$^{3/2}$</td></tr>
<tr><td rowspan="5">Formability</td><td rowspan="5">Strain aging characteristics</td><td colspan="3" rowspan="3"></td><td colspan="12">Strain aged impact test</td></tr>
<tr><td colspan="6">Strain 3%, 250°C × 1h</td><td colspan="6">Strain 5%, 250°C × 1h</td></tr>
<tr><td colspan="2">vE_{-60}≧4.8*1 (kgf·m)</td><td colspan="2">vT_S≦−60*1 (°C)</td><td colspan="2">vT_E (°C)</td><td colspan="2">vE_{-60}≧4.8*1 (kgf·m)</td><td colspan="2">vT_S≦−60*1 (°C)</td><td colspan="2">vT_E (°C)</td></tr>
<tr><td rowspan="2">L</td><td colspan="2">1/4 t</td><td colspan="2">22.2</td><td colspan="2">−82</td><td colspan="2">−82</td><td colspan="2">17.2</td><td colspan="2">−72</td><td colspan="2">−73</td></tr>
<tr><td colspan="2">1/2 t</td><td colspan="2">23.5</td><td colspan="2">−100</td><td colspan="2">−97</td><td colspan="2">21.0</td><td colspan="2">−97</td><td colspan="2">−94</td></tr>
<tr><td rowspan="3">Weld-ability</td><td>Bead on plate test</td><td colspan="3">HV</td><td colspan="6">397 (at 0°C)</td><td colspan="6">387 (at 50°C)</td></tr>
<tr><td rowspan="2">Y-groove restriction cracking test</td><td colspan="3">Atmosphere</td><td colspan="12">30°C × 80%</td></tr>
<tr><td colspan="3">Results</td><td colspan="12">No cracks at 100°C</td></tr>
</table>

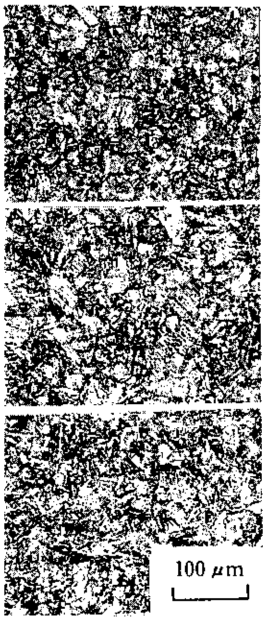
*1 Aimed value

Table 2 Mechanical properties of SAW joint (Heat input: 45 kJ/cm)

Tensile properties				Bend test (R=2t, 180°)		vE_0 (kgf·m)		vE_{-45} (kgf·m)	
Location	TS (kgf/mm^2)	El (%)	Fracture position	Side bend	Surface bend	WM	FL	WM	FL
F side	102	20	HAZ	Good	Good	10.0	20.2	8.2	16.3
B side	103	21	HAZ	Good					

Table 3 Mechanical properties SMAW joint (Heat input: 18 kJ/cm)

Tensile properties				Crit. CTOD δ_c at 0°C (mm)	vE_0 (kgf·m)		vE_{45} (kgf·m)	
Location	TS (kgf/mm^2)	EI (%)	Fracture position		WM	FL	WM	FL
F side	99	36	WM	0.739	7.0	21.0	7.0	9.1
B side	99	35	WM					


(a) Surface

(b) 1/4 t

(c) 1/2 t

Photo 2 Micrographs of 100-mm-thick HT100 kgf/mm^2 steel plate

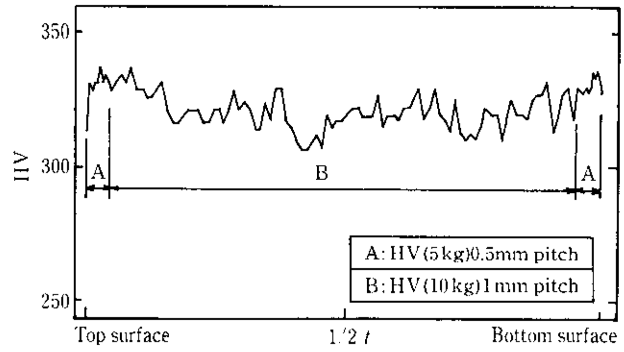


Fig. 1 Hardness distribution on through-thickness direction (Base metal)

4.3 Weldability

Maximum hardness H_{max} was found to be 397 at an initial temperature of 0°C. The preheating temperature for preventing weld cracking in the oblique Y-groove restraint weld cracking test (applicable to SMAW) was 100°C.

From these test results, it was found that this steel plate has the same excellent weld cracking resistance as the HT 80-kgf/mm^2 steel. In the window-type restraint weld cracking test of lateral cracking which occurs in weld metal, it was confirmed that no cracking occurred in the SAW welding at a preheating interpass temperature of 125 to 150°C.

4.4 Welded Joint Performance

Narrow-gap welded joints were produced by SAW, SMAW, MIG, and TIG welding, taking into consideration the use of heavy section material and basic joint performance and brittle crack initiation toughness were investigated. It was found that all four types of joints are of satisfactory reliability.

4.5 Performance Comparison with HT 80-kgf/mm^2

The performance of the newly-developed steel was compared with 150-mm-thick HT 80-kgf/mm^2 steel plate, with the results shown in **Figs. 2** and **3**, which indicate that the new steel has performance equal or superior in both base-metal toughness and weldability to that of HT 80 kgf-mm^2 steel.

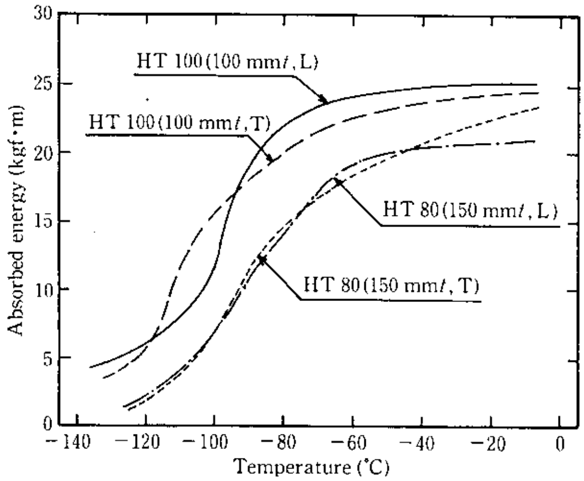


Fig. 2 Comparison of transition curve between HT100 and HT80 kgf/mm^2 steel plates

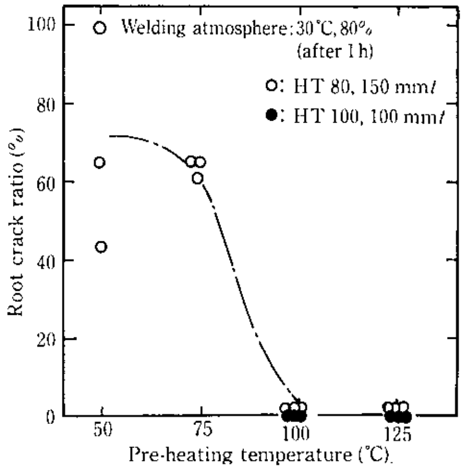


Fig. 3 Comparison of Y-groove restriction cracking test results between HT100 and HT80 kgf/mm steel plates

References

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