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YS500N/mm^2 High Strength Steel for Offshore Structures with Good CTOD Properties at Welded Joints

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Abstract

Nippon Steel was the first in the world to develop YS 500 N/mm^2 high strength offshore structural steel that also has excellent CTOD properties. Increasing strength led to increased Ceq and P$_{cm}$. Therefore, to establish both high strength of YS 500 N/mm^2, and CTOD properties at welded joints in conventional steel was difficult. Nevertheless, it was managed to be possible to increase the strength and toughness under suppressing the Ceq and P$_{cm}$ increase. This was achieved by setting up proper plate manufacturing process (TMCP) and strictly controlling TMCP conditions. Furthermore, the newly developed technology (HTUFF®) was applied to improve HAZ toughness in addition to the conventional measures for reducing martensite-austenite constituent, suppressing local brittle zones and utilizing intragranular ferrite. Through these measures, compatibility was achieved for both high strength (YS 500 N/mm^2) and good properties at welded joints (CTOD at –10℃). As a result, over 50,000 tons of HTUFF high strength offshore structural steels have been mass-produced thus far.

1. Introduction

Generally, offshore structural steels require superior low temperature toughness for the base metal and the welded joints in view of the need for prevention of brittle failure. Particularly, there have been requiring not only Charpy impact properties, but also CTOD (crack tip opening displacement) properties subject to the local brittle zones (hereinafter referred to as ‘LBZ’). Therefore, the establishment of high toughness and high strength through fining the microstructure of HAZ (heat affected zone), and the reduction of LBZ or the suppression of its creation has been a one of the major issues.

In the past, for steel that guaranteed CTOD properties at welded joints, titanium-nitride (TiN) steels and titanium-oxide (TiO) steels were developed. There have also been steels with yield strengths (YS) of 420 N/mm^2 that have been developed and seen actual application[1)]. Conventionally, the demand on welded joints toughness was generally –10°C, however, in recent years environments for offshore structures facilities (and equipment) have expanded to include the frigid sea areas. There have recently been cases in which CTOD properties of extremely low temperatures below –35°C, such as the Sakhalin gas project. Already, development of YS 355, YS 420 N/mm^2 steels with good COTD properties at welded joints under extreme low temperature have been completed[2, 3)]. On the other hand, with a background of intense energy demands worldwide witnessed in the recent years, offshore structures have become larger, which comes with an increased need for lighter weights. Steel materials now require not only

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high strengths but also toughness at low temperature. Of particular note, for the GRANE project in the North sea, YS 500 N/mm^2 class steel with –10°C CTOD properties at welded joints was planed to be applied for the upper portion of the structure instead of the conventional YS 420 N/mm^2 class to reduce the structure weight.

To increase the strength of steel, normally an increase in the chemical components is unavoidable. While there is a trend for degradation of low temperature toughness of both base material and welded joints, weldability properties also are mal-affected. For that reason, it has been a complex issue to enable the stable manufacturing of steel plates that comprise both the highest ranks of YS 500 N/mm^2 class, as well as –10°C CTOD properties at welded joints when only conventional technologies can be applied.

For that reason, Nippon Steel developed a new HAZ toughness technology of "HTUFF® (Super High HAZ Toughness Technology with Fine Microstructure Imparted by Fine Particles)" in continuation from its TiO technology4). This employs the fine oxide particles that exert the pinning effects. These particles are firmly stable even at high temperatures such as those nearing the welding fusion lines. These fine oxides contribute to realize finer HAZ microstructures than in conventional TiN or TiO steel. Applying this new technology, micro-alloying technology and TMCP (thermo-mechanical control process) have attained both high strength and high toughness on base metal and at welded joints. Then YS 500 N/mm^2 class offshore structural steels have good low temperature CTOD properties were developed. This document reports on the results of those developments and the results of actual manufacturing.

2. Development Targets

See **Table 1** Chemical compositions and mechanical requirements of YS 500 N/mm^2 offshore structural steel for details on the main specifications for the base metal and welded joints. The GRANE project of the North Sea that was the target for this development, employed YS 500 N/mm^2 for the offshore structural steel. This was the first application of this type in the world. Specifications for this steel were set based on EN-10225 YS 460 N/mm^2 steels and included NORSOK standards. The strength range was set at YS 80 N/mm^2; tensile strength (TS) was set at 100 N/mm^2. These narrow specifications were to ensure over-matching of the weld metal (WM) while not had been able to complete the high strengths of welding developments.

3. Characteristics of the YS 500 N/mm^2 Offshore Structural steels

3.1 Chemical compositions and manufacturing method

In order to satisfy both the high strength level of YS 500 N/mm^2 and the high toughness level of the impact of –40°C and –10°C CTOD, it is indispensable to utilize the various technologies accumulated to present. Specifically, of course, steel making technologies from scouring to solidification such as oxidizing, secondary refining, control of non-metallic particles, or center segregation control, as well as TMCP technology and micro-alloying technology in plate processing are all required for maximizing their effects. While employing Nb and Ti, strictly controlling the various TMCP conditions from slab reheating to plate cooling, high strength and high

Table 1 Chemical compositions and mechanical requirements of YS 500 N/mm^2 offshore structural steel

Chemical composition

	(mass%)									(mass%)				(ppm)			(mass%)
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	Ti	Al	N	B	Ca	P_{cm}
Min.	–	–	–	–	–	–	0.50	–	–	–	–	–	–	–	–	–	–
Max.	0.14	0.55	1.75	0.020	0.007	0.60	1.00	0.25	0.25	0.040	0.080	0.025	0.055	100	5	50	0.22

P_{cm}=C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

Mechanical properties of base metal

1. Tensile test

Thickness (mm)	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)	YS/TS ratio (%)
t ≤ 16	500/580	600/700	≥ 17	≤ 93
t > 16				≤ 90

2. Charpy V-notch impact test

Thickness (mm)	Test temperature (°C)	Location of specimen	Energy (J)
t ≤ 40	– 40	Sub-surface	≥ 42/60 (min./ave.)
t > 40	– 40	Sub-surface and mid-thickness	

3. Through thickness tensile test

Thickness (mm)	Tensile strength (N/mm^2)	Reduction of area (%)
All thickness	≥ 480	≥ 25/35 (min./ave.)

Fracture toughness of welded joints

Charpy test				CTOD		
Test temperature	Location of specimen	Notch location	Energy	Test temperature	Notch location	δ
– 40°C	Cap	Weld metal	Min. ≥ 42J	– 10°C	Weld metal (WM)	≥ 0.25mm
	Mid-thickness	Fusion line (FL)	Ave. ≥ 60J		Grain coarsend HAZ (GCHAZ)	
	Root	FL+2mm(HAZ)			Subcritical / intercritical HAZ boundary (SC/IC HAZ)	
		FL+5mm(HAZ)				

toughness base metal was achieved without increasing the chemical compositions (especially Ceq, P_{cm}) to more than what was required.

Fig. 1 shows the manufacturing process; **Table 2** shows the representative chemical compositions. While in the refining and casting process, it is necessary to ensure a high level of cleanliness and to control the center segregation by soft reduction technique using divided roles[5)]. TMCP conditions were properly arranged and strictly controlled from reheating to accelerated cooling. The reheating temperature was designed to ensure that the added Nb was thoroughly dissolved and coarsening of austenite grain size was suppressed by Ti (C, N).

See **Table 3** for the main measures for improving HAZ toughness. While HTUFF technology is a newly developed HAZ toughness improving technology. At the same time, silicon and aluminum were suppressed for reducing MA (martensite-austenite constituent), and an appropriate stoichiometric balance between titanium and nitrogen was achieved to avoid titanium carbides precipitates.

3.2 Mechanical properties of the base metal

Steel plates were manufactured with the specifications outlined in Table 1 for the GRANE project and the KVITEBJORN project in the North Sea. Approximately 7,000 t of these YS 500 N/mm^2 offshore structural steels of the thickness up to 70 mm were mass-produced. See **Fig. 2** for details on the mechanical properties of the mass-produced steel plates. While this shows that adequate strength was achieved. Moreover, YS 80 N/mm^2 range and TS 100 N/mm^2 range were both achieved. Also, good Charpy impact properties were achieved not only at 2mm under the top surface but also at mid-thickness even at – 40°C. **Fig. 3** shows the microstructure of 70mm-thick plate. By properly arranging the TMCP conditions and strictly managing them, fine ferrite-bainite structures were attained in all regions through thickness direction. Thus, good quality mechanical properties were achieved.

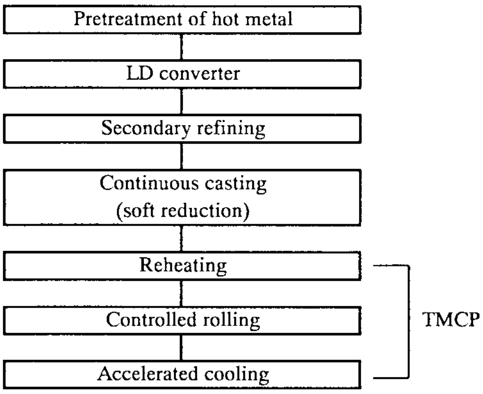


Fig. 1 Manufacturing process

3.3 Mechanical properties at welded joints

3.3.1 Mass-production stability of HTUFF technology

With regard to the pinning effect caused by fine developed particles which are the essential point for HTUFF technology, stability in the mass-production was verified by applying heat cycle tests. Test conditions were reheating to 1400°C and holding for 60 seconds and following to be quenched to freeze the microstructures at high-temperature. This test was performed for each tapped steel heat. **Fig. 4** shows the measurement results of austenite grains sizes of heating tests on the mass-produced HTUFF offshore structural steels. The grain growth of austenite is quite strongly suppressed to 200 μm or less, in spite of under extremely severe conditions (In conventional steel, austenite grains can coarsen over 400 μm). It suggests that the strong pinning effects have also been achieved in mass-production.

3.3.2 Mechanical properties of the actual welded joints

The HAZ properties of the newly developed steel plates of maximum thickness of 70mm were examined. The tests were conducted under two heat-input (H.I.) conditions, 0.7kJ/mm of FCAW (flux cored arc welding) and 3.5kJ/mm of SAW (submerged arc welding). Groove shapes and welding conditions are shown in **Fig. 5**. PWHT (post weld heat treatment) (580°C for 4 hours) joints were also tested in 3.5kJ/mm of SAW. **Fig. 6** shows the hardness distribution across the SAW joints. Softening in the HAZ was small and the weld metal was overmatched to the base metal. **Fig. 7** shows the results of CTOD tests at –10°C for welded joints. The notch locations were at the weld metal (WM, 2mm apart from fusion line), grain coarsened HAZ (GCHAZ) and subcritical HAZ / intercritical HAZ boundary (SC/IC HAZ) in accordance with EN-10225. Excellent CTOD properties were achieved at each HAZ location for all welding conditions, with CTOD δ_c values exceeding 0.25mm. Charpy impact test specimens were taken from 2mm under the top surface (cap), the mid-thickness and 2mm under the bottom surface (root). **Fig. 8** shows the Charpy impact test at –40°C results for the welded joints. The average values of the absorbed energies exceeded 150J and the minimum values exceeded 100J in all tests.

Table 2 Typical chemical compositions of YS 500 N/mm^2 offshore structural steel

	(mass%)							(mass%)
	C	Si	Mn	P	S	Al	Othres	P_{cm}
YS500N/mm^2 developed steel	0.09	0.15	1.60	0.005	0.002	0.003	Cu, Ni, Nb, Ti, Mg	0.21

Table 3 Measures of improving HAZ toughness

Measures	Purpose
Ti-killed and fix the nitrogen	Improving matrix toughness and nucleation IGF
Low silicon	Decreasing LBZ (MA)
Low aluminum	Enhancing nucleation IGF and decreasing LBZ (MA)
Control the Ti-N balance	Suppressing TiC embrittlement
Low impurity elements	Improving matrix toughness and decreasing LBZ
Add the magnesium	Refining HAZ microstructure (utilizing HTUFF technology)
Low P_{cm}	Improving matrix and HAZ toughness

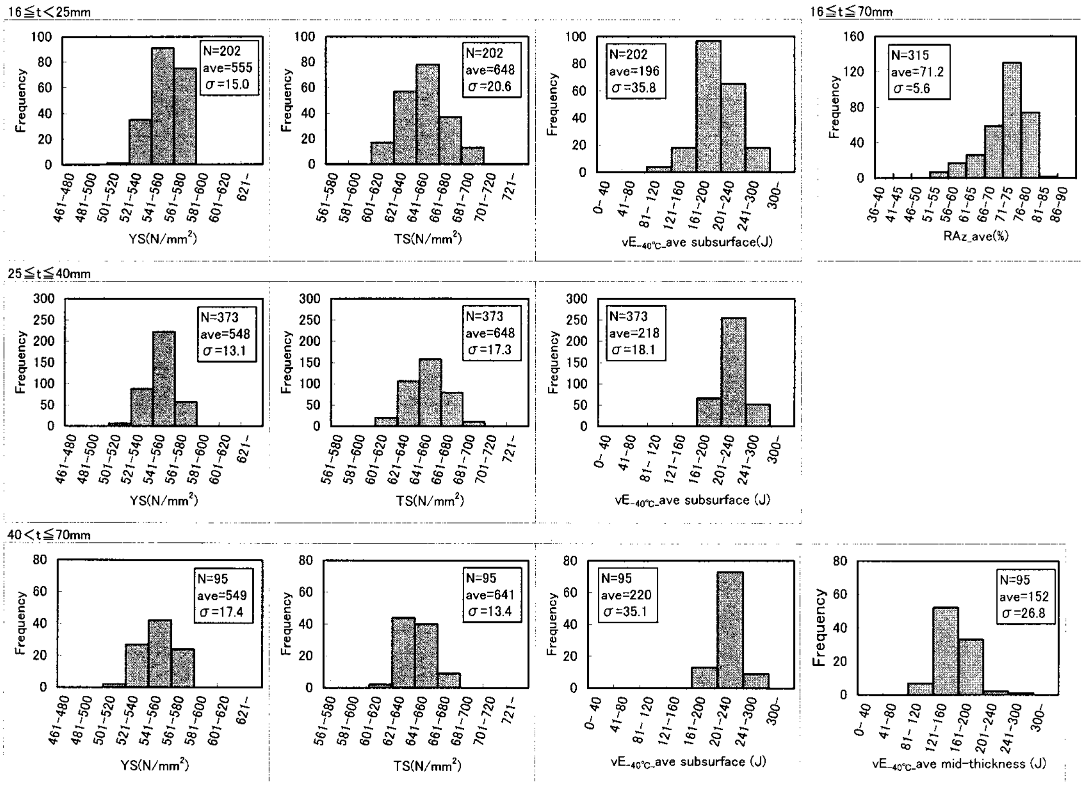


Fig. 2 Mechanical properties of base metal

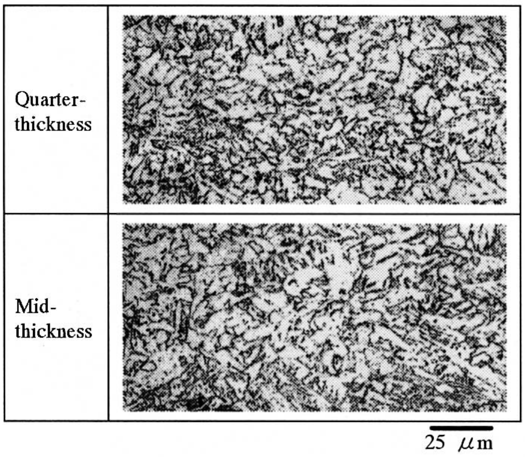
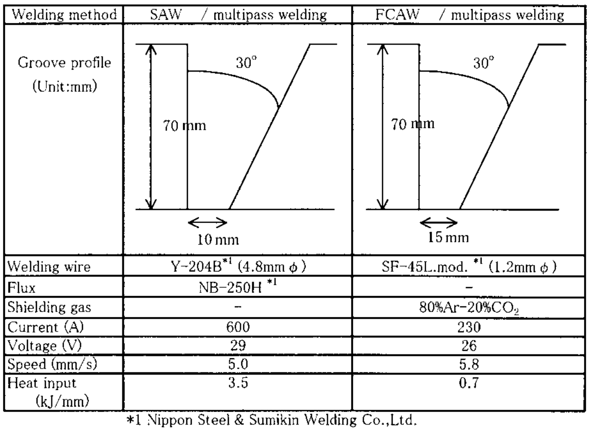


Fig. 3 Microstructures of YS 500 N/mm² steel plate of 70mm thickness



Welding method	SAW / multipass welding	FCAW / multipass welding
Groove profile (Unit:mm)	30° 70 mm 10 mm	30° 70 mm 15 mm
Welding wire	Y-204B*1 (4.8mm φ)	SF-45L.mod. *1 (1.2mm φ)
Flux	NB-250H *1	-
Shielding gas	-	80%Ar-20%CO$_2$
Current (A)	600	230
Voltage (V)	29	26
Speed (mm/s)	5.0	5.8
Heat input (kJ/mm)	3.5	0.7

*1 Nippon Steel & Sumikin Welding Co.,Ltd.

Fig. 5 Welding condition

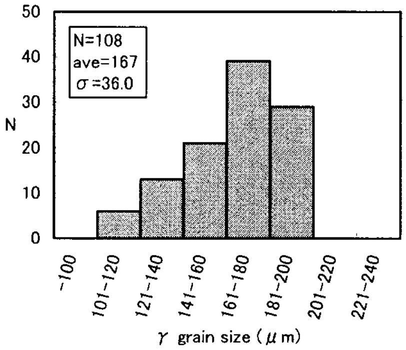


Fig. 4 γ grain size reheated at 1400°C for 60 s

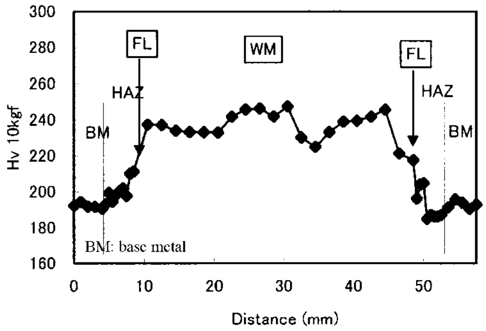


Fig. 6 Hardness distribution across the welded joints

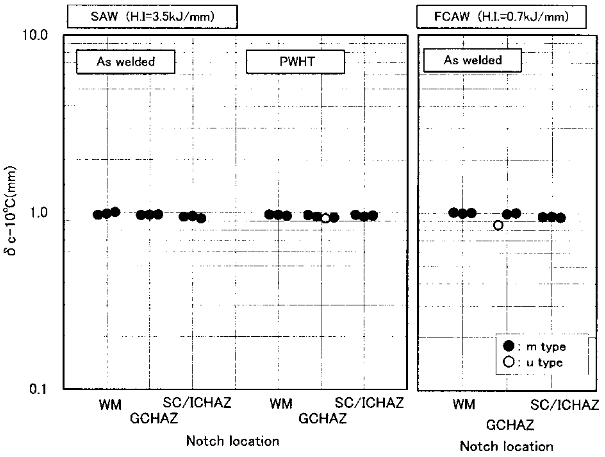


Fig. 7 CTOD test results of welded joints

Tables 4 and **5** show the CTS (controlled thermal severity)[6] and y-groove[7] weldability test results. The developed steel plates have good weldability and are free from pre-heating before welding thanks to control at low P_{cm}.

4. Conclusions

1) High-strength and high-toughness steel for offshore structures was commercially mass-produced by the application of the new HAZ microstructure fining technology. The newly developed steel satisfies $YS \geqq 500N/mm^2$, $TS \geqq 600N/mm^2$ and exhibits excellent CTOD properties at welded joints.
2) The newly developed steel was produced by strictly controlled TMCP conditions. The chemical compositions were also optimized and controlled in narrow range. This ensures that P_{cm} is suppressed to no more than 0.22% in YS 500 N/mm^2 high strength steels. Low P_{cm} makes for good weldability in the newly developed steels.

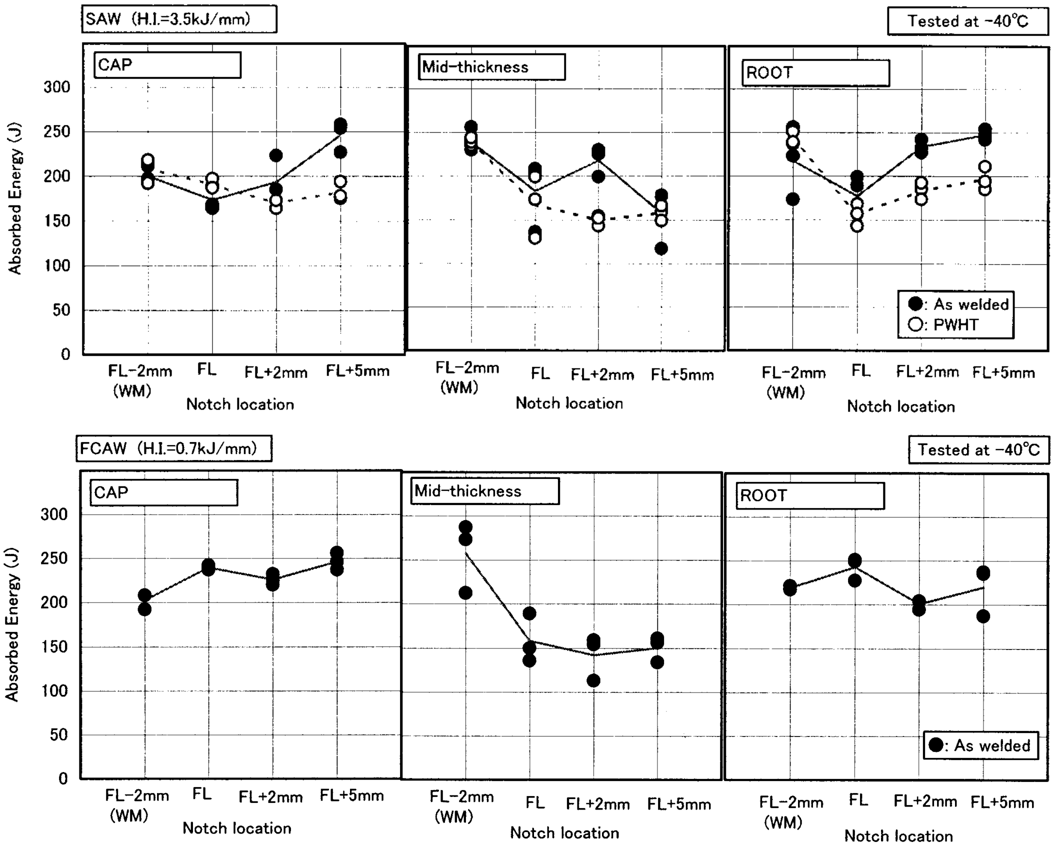


Fig. 8 Charpy impact test results of welded joints

Table 4 CTS weldability test results

Preheat temperature (°C)	Hardness			Crack evaluation
	Hv load : 5kgf			
	Min.	Max.	Ave.	
25	278	328	307	No cracking
50	277	329	304	No cracking
75	283	320	304	No cracking

Shielded metal arc welding, 1.0kJ/mm

Table 5 y-groove weldability test results

Preheat temperature (°C)	Surface cracking ratio (%)						Section cracking ratio (%)						Root cracking ratio (%)					
	1	2	3	4	5	Average	1	2	3	4	5	Average	1	2	3	4	5	Average
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Shielded metal arc welding, 1.7kJ/mm

Table 6 Supply records of HTUFF offshore structural steels

Production period	Project name	Area	YS class (N/mm^2)	Toughness of welded joint		Quantity (kton)
				Charpy	CTOD	
2000-2001	Bayu Undan	Timor Sea	460	– 40°C	– 10°C	20.4
2000-2001	Grane	North Sea	500	– 40°C	– 10°C	4.0
2001	Kvitebjorn	North Sea	500	– 40°C	– 10°C	3.0
2001-	ACG	Caspian Sea	460	– 40°C	– 10°C	17.5
2002-2003	Thunder Horse	Gulf of Mexico	500	– 40°C	Not required	0.6
2002-2003	Western Libya	Mediterranean Sea	460	– 40°C	– 10°C	5.2
						Total 50.7

3) The newly developed steels have been mass-produced for various offshore structures to a total of over 50,000 tons (see **Table 6**).

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