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Development of TS780 N/mm^2 Class Steel Plate with Low Reheat Cracking Susceptibility

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Abstract:

TS780 N/mm^2 class steel plate with low reheat cracking susceptibility during post weld heat treatment (PWHT: Post-weld heat treatment) of welded structures has been developed. Reheat cracking often becomes a problem for high strength steels of 780 N/mm^2 or higher class because the high strength steels usually contain carbide-forming elements such as Cr, Mo and V, which precipitate during PWHT and enhance the cracking. The reheat cracking susceptibility has been reduced by the alloy design in combination with reduction in impurity elements (P and S) and addition of Ca which forms sulfide. The developed steel was produced in an actual plate mill, and achieved excellent low reheat cracking susceptibility in the C-ring test, which is one of the methods evaluating reheat cracking.

1. Introduction

In recent years, high strength steels of 780 N/mm^2 class have been applied to welded structures, including pressure vessels, bridges, and buildings, in response to the diversification and enlargement of the structures. Post-weld heat treatment (PWHT) is applied to welded structures in order to reduce welding residual stress, improve the performance of the welded zone, and remove hydrogen gas. However, when PWHT is applied to high strength steels, deterioration of strength and toughness and intergranular cracking along the prior austenite grain boundary in the coarse grain heat affected zone (CGHAZ) of the weld toe often become problems [1]. This type of cracking is called reheat cracking or stress relief cracking and has been recognized as a problem which easily occurs in high strength steels of 780 N/mm^2 class or higher [2].

Rules and standards for PWHT of steel plates are described in the ASME standard and technical standards in Japan, and are also described for high strength steels. The table UHT-56 of ASME Sec. VIII Div. 1 UHT-56 specifies PWHT conditions for tempered high strength steels including TS780 N/mm^2 class steel, and also includes notes about temper-embrittlement in PWHT. The Japanese JIS Z 3700 standard provides a heat treatment method for use after welding TS590 N/mm^2 and lower class steels, but does not describe the method for TS780 N/mm^2 class steel in detail. According to the technical guideline [1], whether PWHT is performed or not is decided on a case-by-case basis, and careful consideration of the PWHT conditions is required for TS780 N/mm^2 class steel due to deterioration of toughness of the heat affected zone (HAZ) and occurrence of reheat cracking. In the Japanese Technical Standards for Hydraulic Gates and Penstocks [3], PWHT is generally not performed for SHY 685 NS-F, which is a TS780 N/m^2 class steel specified in the JIS standard, due to risk of reheat cracking, and

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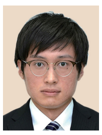

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Table 1 Target chemical compositions and mechanical properties for developed steel plate

(mass%)

Thickness (mm)	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	*C*eq	ΔG	P_{SR}
t≦50	≦0.14	≦0.55	≦1.50	≦0.015	≦0.015	≦0.50	0.3～1.50	≦0.80	≦0.60	≦0.05	≦0.005	≦0.53	≦0.31	≦0.16
50<t≦75												≦0.57		

Thickness (mm)	Tensile properties				Charpy impact properties	Reheat cracking test (%)
	Specimen	YS (MPa)	TS (MPa)	El (%)	$vE_{-40°C}$ (J)	
t≦50	JIS 5	≧685	780～930	≧16 (6≦t≦16) ≧24 (16<t)	≧27 (Each) ≧47 (Ave.)	0
	JIS 4			≧16 (20<t)		
t>50	JIS 5	≧665	760～910	≧24		
	JIS 4			≧16		

$Ceq = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14$, $\Delta G = Cr + 3.3Mo + 8.1V - 2$, $P_{SR} = Cr + Cu + 2Mo + 10V + 7Nb + 5Ti - 2$,
YS: Yield strength, TS: Tensile strength, TS: Tensile strength, $vE_{-40°C}$: Absorbed energy at −40°C

when it is performed, it is necessary to consider the PWHT conditions carefully. Although PWHT of TS780 N/mm^2 class steel is regulated by some standards, close attention is required when performing post-weld heat treatment. Therefore, the development of a TS780 N/mm^2 class steel which maintains high strength and high toughness after PWHT and has low reheat cracking susceptibility has been desired.

JFE Steel developed a TS780 N/mm^2 grade steel with low reheat cracking susceptibility without deterioration of strength and toughness after PWHT. This paper introduces the features of the developed steel and the performance of the steel plates.

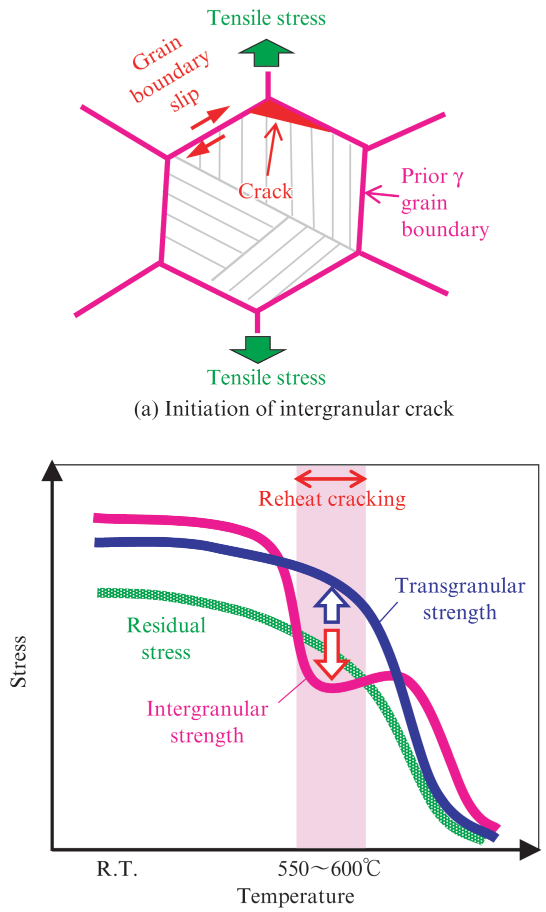
2. Target Performance

The target chemical composition and mechanical properties of the developed steel are shown in **Table 1**. The development targets are strength and toughness equivalent to SHY 685 NS in accordance with JIS G 3128. The target reheat cracking sensitivity is to keep the generally proposed reheat cracking susceptibility indexes ΔG and P_{SR} [4, 5] below those of the conventional steel, and to prevent reheat cracking in the reheat cracking reproduction test by the C-ring test described later.

3. Alloy Design of Developed Steel

3.1 Principle of Reheat Cracking

A schematic diagram of the mechanism of reheat cracking is shown in **Fig. 1**. The mechanisms of reheat cracking is as follows [6, 7]. When the temperature is increased by PWHT and transgranular strength relatively exceeds intergranular strength due to an increase in transgranular strength by precipitation strengthening and a decrease in intergranular strength by segregation of impurity elements, relaxation of welding residual stress by plastic deformation of the grains is difficult. As a result, grain boundary sliding occurs, deformabil-



(a) Initiation of intergranular crack

(b) Temperature dependence of intergranular and transgranular strength

Fig. 1 Schematic illustration of mechanism for reheat cracking ity around the grain boundary decreases due to segregation of impurity elements, and cracks are generated in the grain boundary. This type of crack is a reheat crack. Welding residual stress and the chemical composition and microstructure of the steel are involved in the occurrence of reheat cracking, and control of these three elements is important for preventing the reheat cracking.

Reheat cracking prevention methods are considered from the viewpoints of structural design, the welding procedure, and materials. From the viewpoint of structural design, a weld structure with less stress concentration is effective, and from the viewpoint of the welding procedure, stress relaxation by smoothing the weld toe and improvement of the material quality by the temper bead method and buttering method are effective. However, these methods increase the construction period and cost. Therefore, reheat cracking prevention methods from the viewpoint of materials are desired.

Reduction of alloying elements which increase transgranular strength and reduction and fixation of impurity elements which decrease grain boundary strength are effective strategies from the viewpoint of materials [8, 9]. The elements which increase intragranular strength are carbide forming elements such as Cr, Mo, V, and Nb. Reheat cracking susceptibility can be evaluated by the reheat cracking susceptibility indexes P_{SR} and ΔG [4, 5].

The material microstructure also affects reheat cracking susceptibility. It has been pointed out that microstructures with larger grain sizes are more susceptible to reheat cracking, and those with lower hardness are less susceptible to reheat cracking. It is considered that reheat cracking is most likely to occur in the CGHAZ, where prior austenite grains tend to be coarsened and clear prior austenite grain boundaries remain.

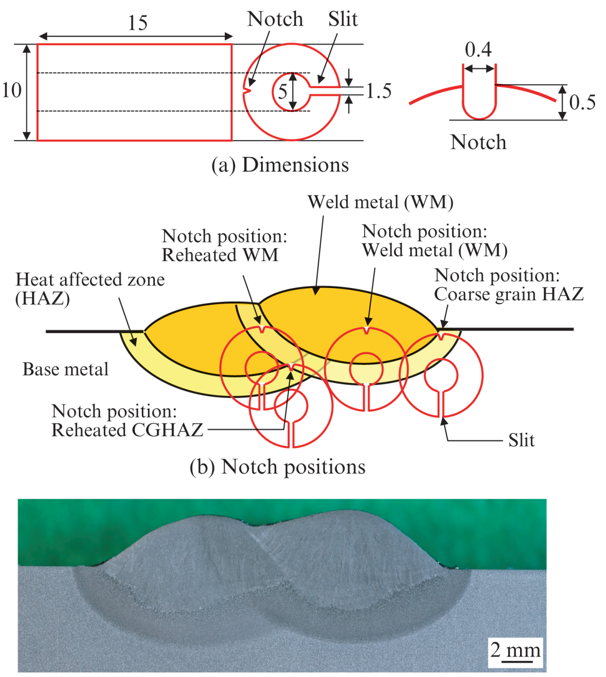
In order to maintain the mechanical properties of TS780 N/mm^2 grade steel, the developed steel has the same values of the reheat cracking susceptibility indexes (P_{SR} and ΔG) as the conventional steel, which have a large influence on strength, and reheat cracking susceptibility is reduced by reducing impurity elements.

3.2 Reheat Cracking Test

In the reheat cracking evaluation test, it is important to appropriately simulate the welding residual stress and the microstructure of the HAZ at the initiation site of reheat cracking. In this development, a C-ring test [7], which is one reheat cracking evaluation method, was used. **Figure 2** shows the shape of the specimen and the sampling position. In the present test, C-ring specimens were taken from the welded part of two beads on plate to evaluate the various microstructures of the HAZ. Photographs of the specimen before and after welding are shown in **Photo 1**. The slit on the opposite side from the notch was attached and fixed by welding, and tensile stress simulating welding residual stress was applied to the notch bottom. The U-notch bottom, which is the evaluation position for reheat cracking, was set at the following four locations.

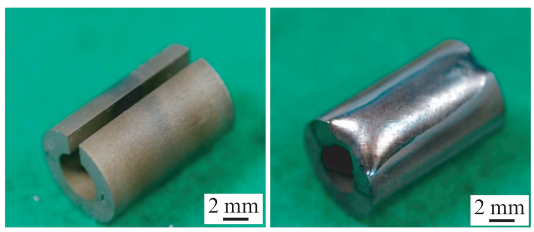
1) Coarse grain heat affected zone, where reheat cracking susceptibility is considered to be the highest (1st Bead CGHAZ)
2) Coarse grain heat affected zone reheated by the 2nd bead
   (1st Bead CGHAZ + 2nd Bead HAZ End)
3) Weld metal (1st Bead WM)
4) Weld metal reheated by the 2nd bead
   (1st bead WM + 2nd bead HAZ center)

The stress generated in the C-ring test has been reported in the past literature [7, 11], but many details, such as the local stress distribution, were unclear. Therefore, a FEM stress analysis was performed to



(a) Dimensions
(b) Notch positions
(c) Macrostructure of welding beads on the plate

Fig. 2 C-ring test specimen



(a) Before welding (b) After welding

Photo 1 Appearance of C-ring test specimen determine the slit width to be applied in this evaluation test. The C-ring specimen model used in the analysis is shown in **Fig. 3**, and the stress-strain curve is shown in **Fig. 4**. The physical property conditions used in this analysis, such as strength and thermal conductivity, are measured values of HT 780 and values in the literature [12]. The boundary conditions and analysis procedure for the FEM analysis are shown in **Fig. 5**. First, displacement was applied in the Y direction until the initial slit width became 0.05 mm, after which the center of the outside of the ring was restrained (1. Restraint), and a heat source of 1 600°C was applied to the weld (2. Welding). The entire model was then air-cooled to 30°C (3. Cooling), the restraint applied to the outside of the ring was released (4. Release restraint), and the generated stress at this time was determined. An example of the analysis result is shown in **Fig. 6**. This result is consistent with the previous literature, in which high stress is generated locally around the notch bottom, and cracks are generated from just below the notch. The relationship between the slit width and the maximum equivalent stress (Mises stress) at the notch bottom is shown in **Fig. 7**. As the slit width increases, the maximum equivalent stress and the risk of reheat cracking also increase. In the specimen with a 1.5 mm slit width, residual stress close to the yield strength of the material remains at room temperature, and the risk of reheat cracking is high. Therefore, in this development, a C-ring test with a slit width of 1.5 mm was carried out, and unless a clear crack was observed in the cross section by optical microscopy, it was judged that the steel had low reheat cracking susceptibility.

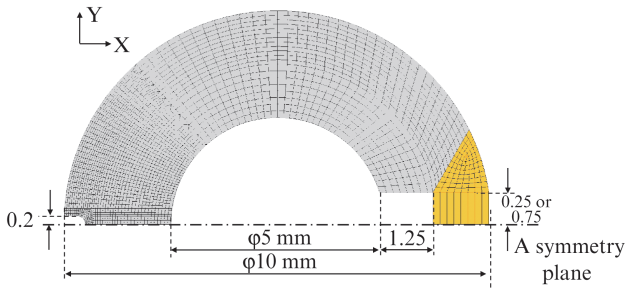


Fig. 3 FEM mesh model of C-ring test specimen

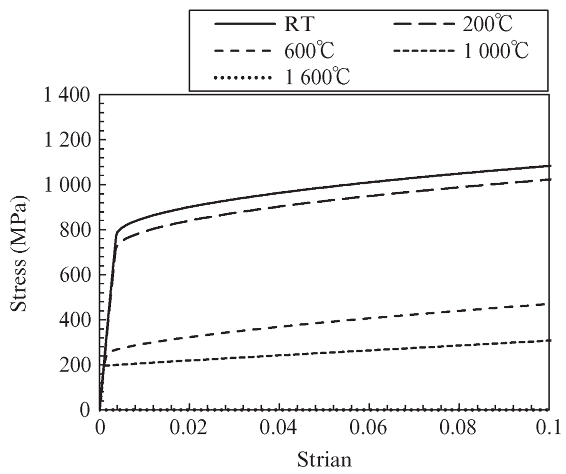


Fig. 4 Examples of stress-strain curves for FEM analysis

3.3 Effect of Chemical Composition on Reheat Cracking Susceptibility

A C-ring test of the conventional TS780 N/mm^2 class steel was carried out under PWHT conditions of 580°C × 4 h, and reproducibility of the reheat cracking evaluation test was confirmed. In this test, three C-ring tests were conducted. The presence or absence of cracks was confirmed in three sections of each test piece, and the occurrence rate of cracks in nine sections

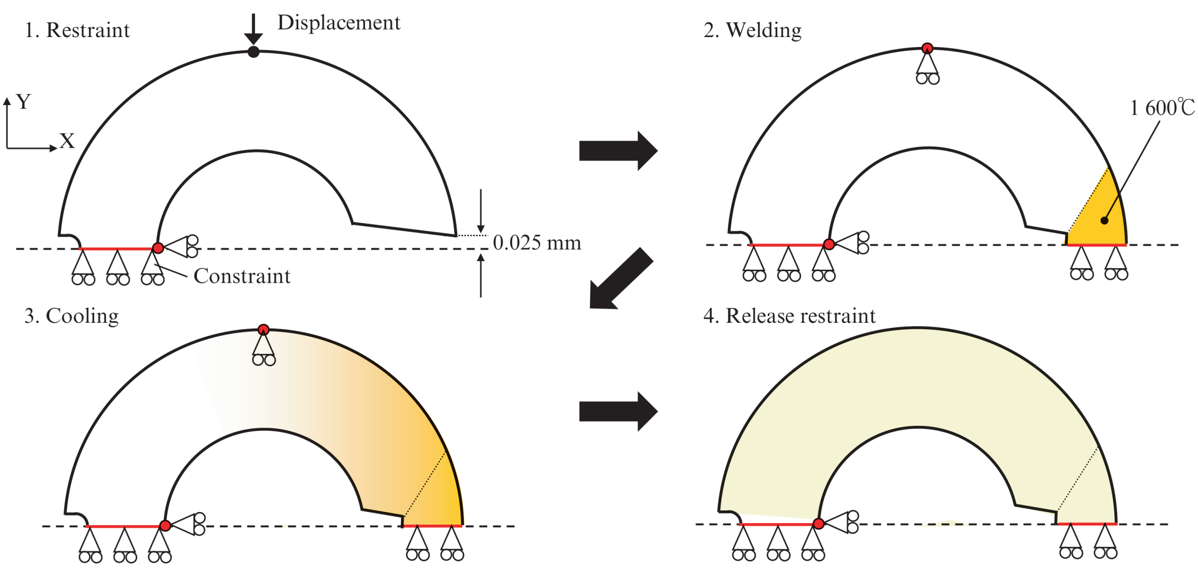


Fig. 5 FEM analysis flow

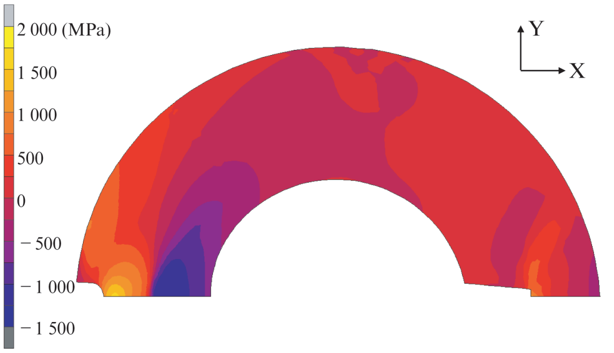


Fig. 6 Principal stress distribution of C-ring test specimen in Ydirection

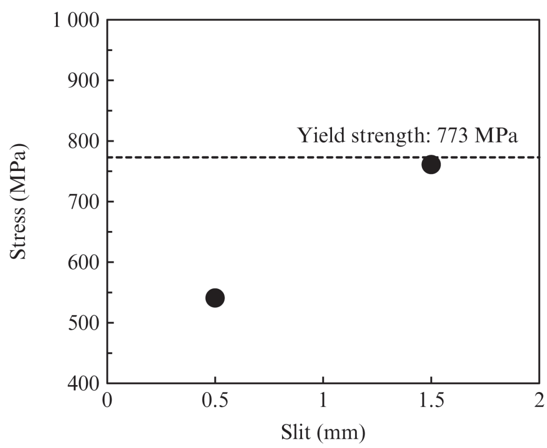
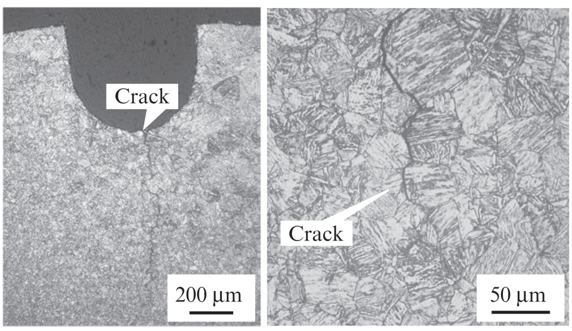


Fig. 7 Effect of slit width on maximum equivalent stress in C-ring specimen

Table 2 Result of C-ring test for conventional TS780 N/mm^2 class steel plate

Notch position	Crack ratio (%)
WM	0
Reheated WM	0
CGHAZ	100
Reheated CGHAZ	0



(a) Notch bottom (b) Crack path

Photo 2 Cross section of C-ring specimen for conventional steel (Notch position: CGHAZ)

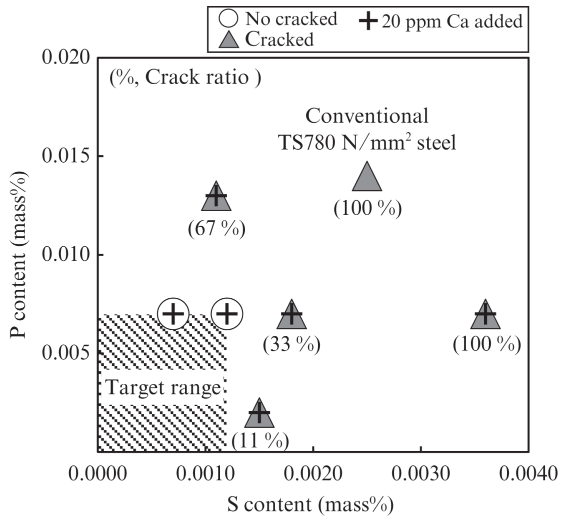


Fig. 8 Effect of P and S content, Ca addition on reheat cracking susceptibility

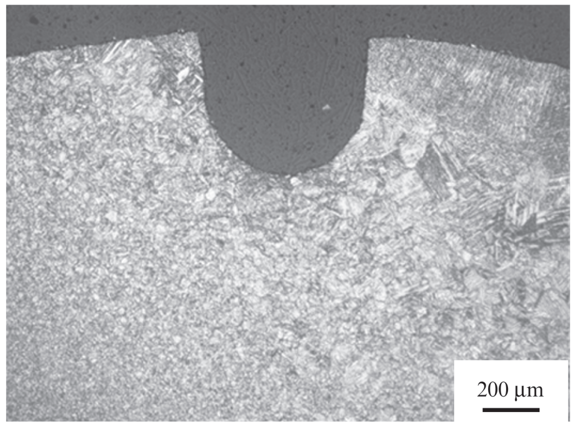


Photo 3 Cross section of notch bottom of C-ring specimens for 0.007% P-0.0012%S-0.0020%Ca steel

in total was evaluated. The C-ring test results are shown in **Table 2**, and the cross-sectional microstructure of a cracked C-ring specimen is shown in **Photo 2**. It was found that reheat cracking occurs only in the CGHAZ, and the cracking propagates along the prior austenite grain boundary from just below the notch. This result agreed with the conventional tendency of reheat cracking and confirmed that reheat cracking can be reproduced by this test.

Next, the effect of impurity elements on reheat cracking susceptibility was investigated on the basis of the conventional TS780 N/mm^2 class steel. The effects of the P and S contents and Ca addition on reheat cracking susceptibility were evaluated by a C-ring test. The results are shown in **Fig. 8**. Addition of Ca and reduction of the P and S contents tend to reduce the occurrence of reheat cracking. Reheat cracking does not occur when Ca is added and the P and S contents are controlled to ≤ 0.007 % and ≤ 0.0012%, respectively.

Table 3 Chemical composition of the developed steel

(mass%)

Thickness (mm)	C	Si	Mn	P	S	Others	Ceq	ΔG	P_{SR}
36, 60	0.11	0.25	0.95	0.003	0.0004	Cu, Ni, Cr, Mo, V, Ti, B, Ca	0.5	0.14	−0.04

Ceq = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15, ΔG = Cr + 3.3Mo + 8.1V-2, P_{SR} = Cr + Cu + 2Mo + 10V + 7Nb + 5Ti − 2

Table 4 Mechanical properties of the developed steel

Thickness (mm)	PWHT	Position	Tensile properties (Specimen: JIS4)				Charpy impact properties		Reheat cracking test (%)
			Direction	YS (MPa)	TS (MPa)	El (%)	Direction	$vE_{-40^\circ C}$ (J)	
36	−	1/4t	T	783	827	24	L	261	0
	580°C×4h			776	824	25		265	
60	−	1/4t	T	782	826	25	L	245	0
	580°C×4h			778	828	25		261	

PWHT: Post weld heat treatment YS: Yield strength TS: Tensile strength El: Elongation
$vE_{-40^\circ C}$: Absorbed energy at −40°C

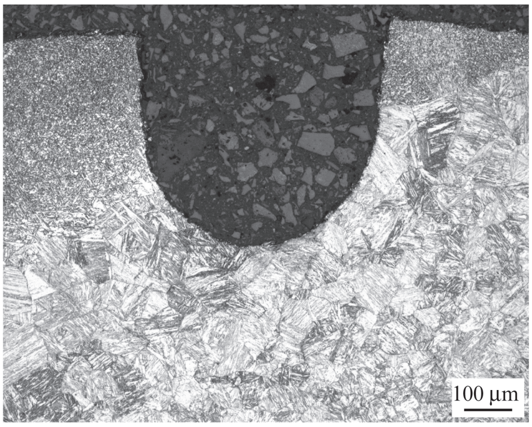


Photo 4 Cross section of notch bottom of C-ring specimens after test for developed steel

A photograph of a C-ring specimen after the test is shown in **Photo 3**. In this test piece, a clear crack like that observed in the conventional TS780 N/mm^2 class steel was not confirmed. Therefore, it was found that improvement of reheat cracking susceptibility can be expected even with the same reheat cracking susceptibility index as that of the conventional TS780 N/mm^2 class steel by using the low P-low S-Ca added alloy design.

4. Features of Developed Steel

4.1 Mechanical Properties of Base Material

The chemical composition of the developed steel is shown in **Table 3**. The basic components are the same as those of the conventional TS780 N/mm^2 grade steel. However, the contents of P and S are reduced as much as possible to reduce reheat cracking susceptibility, and Ca is added. The base metal properties of the developed steel plates with thicknesses of 36 mm and 60 mm produced by the quenching and tempering process are shown in **Table 4**. The developed steel has sufficient strength to satisfy the SHY 685 NS standard before and after PWHT and excellent low temperature toughness at −40°C.

4.2. Reheat Cracking Susceptibility of Developed Steel

The reheat cracking susceptibility of the developed steel was evaluated by a C-ring test using a test piece with a 1.5 mm slit width. The evaluation results are shown in Table 4, and a typical cross-sectional photograph of the test piece after the test is shown in **Photo 4**. Reheat cracking was not observed in the newly developed steel. The results of the test confirmed that the developed steel achieves excellent low reheat cracking susceptibility.

5. Conclusion

A new TS780 N/mm^2 class steel plate with low reheat cracking susceptibility without deterioration of strength and toughness was developed. The developed steel can reduce the risk of reheat cracking when TS780 N/mm^2 grade steel is applied to welded structures subjected to PWHT, and is expected to contribute to reducing the burden of structural design and welding procedures for reheat cracking prevention.

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