Abridged version

KAWASAKI STEEL TECHNICAL REPORT

No.40 (May 1999)

Steinless Steel and Steel Platel

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Kiyomi Araki, Takeshi Kohriyama, Motoshi Nakamura

Synopsis :

Heavy steel plates with thickness of over 150 mm have usually been manufactured by using materials obtained through ingot casting process, in consideration of the internal properties. The possibility of applying a forging process before plate rolling was investigated to secure both homogeneous and sound internal properties by using continuous casting slabs, instead of ingot casting slabs. When a certain annihilation of center porosities is considered, a forging method with reduction in widthwise direction before reduction in thicknesswise direction of slabs was found to be very effective. As a result of the application of this process for TS: 400 MPa class steel, it is concluded that excellent internal properties can be obtained in the manufacture of heavy steel plates with thickness of up to 240 mm (reduction ratio: 1.3).

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Development of Heavy Section Steel Plates with Improved Internal Properties through Forging and Plate Rolling Process Using Continuous Casting Slabs*

Kiyomi Araki
Staff Assistant Manager, Plate, Casting & Forging Control Sec., Technical Control Dept., Mizushima Works

Takeshi Kohriyama
General Manager, Plate Business Planning Dept.

Motoshi Nakamura
Technical Support Sec., Nishi-Nihon District Office, Kawasaki Steel Systems R&D Corp.

Synopsis:

Heavy steel plates with thickness of over 150 mm have usually been manufactured by using materials obtained through ingot casting process, in consideration of the internal properties. The possibility of applying a forging process before plate rolling was investigated to secure both homogeneous and sound internal properties by using continuous casting slabs, instead of ingot casting slabs. When a certain annihilation of center porosities is considered, a forging method with reduction in widthwise direction before reduction in thicknesswise direction of slabs was found to be very effective. As a result of the application of this process for TS: 400 MPa class steel, it is concluded that excellent internal properties can be obtained in the manufacture of heavy steel plates with thickness of up to 240 mm (reduction ratio: 1.3).

1 Introduction

When heavy section steel plates with thicknesses of more than 100 mm are manufactured from continuous casting slabs, the porosities which occur at the final solidification position in slabs tend to remain in the product more easily as the reduction ratio (slab thickness/product thickness) becomes smaller, giving rise to concern over deterioration of the soundness and mechanical properties of the plate. For this reason, numerous studies have been conducted from early date with the aim of improving the internal defects caused by porosities in continuous casting slabs, and thus manufacturing sound heavy section plates.[1-3] These studies proposed processing conditions which close and annihilate porosities by more effective application of plastic strain and compressive stress in the thicknesswise direction at the center of thickness of the plate, using techniques such as heavy reduction rolling with large diameter rolls, low speed rolling, and rolling in which the temperature differential in the thicknesswise direction is deliberately increased. However, in practical operations, there are limits to the equipment specifications and capacity of plate rolling mills. Consequently, in the manufacture of heavy section plates with thicknesses of more than 150 mm, a process using materials obtained through the ingot casting process has generally been applied. In addition, it is known that forging is effective in improving the internal properties of ultra-heavy section steel plates produced from heavy ingots.[4-6]

The authors therefore carried out a study of the manufacture of plates from continuous casing slabs using a forging-plate rolling process and established a technology for manufacturing sound heavy section plates with thicknesses of up to 240 mm, as described in the following.

2 Study of Forging Process by Elastic-Plastic Stress Computer Analysis

Porosities are annihilated by a process in which plastic strain forces the inner surfaces of the porosity into

* Originally published in *Kawasaki Steel Giho*, 30(1998)3, 181–185

Table 1 Condition of elastic-plastic stress calculation

Dimension of slab (mm)	310 × 2 240 × 3 000
Heating temperature (°C)	1 250
Surface temperature at the start of forging (°C)	1 000

Density: 7 700 kg/m^3
Heat conductivity: 23.2 W/mK (at 1 100°C)
Yield point: 0.9 MPa (at 1 100°C)
Young's modulus: 5 676 MPa (at 1 100°C)
Poisson's ratio: 0.3
Thermal expansion factor: 0.000 018/°C (at 1 100°C)
Work hardening coeffiicient: 25.2MPa (at 1 100°C)

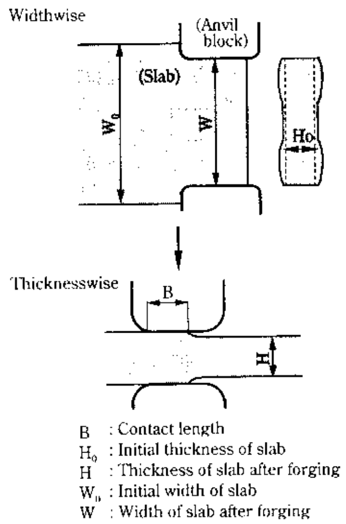

Fig. 1 Schematic diagram of forged continuous casting slab

mutual contact, and the porosity is then annihilated by diffusion and contact pressure.[5] Here, effective forging conditions were studied using an elastic-plastic stress computer analysis program (MARC). Because the center of thickness region is a problem in annihilating the porosities which exist within continuous casting slabs, the plastic strain at the center of thickness position was considered in this analysis. The conditions of the analysis are shown in **Table 1**. Although it is necessary to consider heat removal by the anvil blocks, heat generated by processing, and similar factors related to changes is the temperature of the slab during forging, the analysis was carried out assuming that the internal temperature distribution of the slab at the start of forging remains constant throughout the forging process.

2.1 Forging Conditions

The forging process is shown schematically in **Fig. 1**. The effect of the ratio of the contact length of the anvil blocks (B) and the initial thickness of the slab (H_0), namely, B/H_0, on the amount of plastic strain, and the effect of applying widthwise reduction before forging in the slab thickness direction, were evaluated. The forging conditions used in the analysis (No. 1–6) are shown in **Table 2**. First, for the case of forging reduction only in the slab thicknesswise direction, the effect of B/H_0 (three levels: 0.10, 0.74, 1.06) on the maximum plastic strain was compared when the reduction ratio in the slab thickness direction (H_0/H) was held constant at 1.19. Then, a study was made to determine the effect of performing (as opposed to not performing) widthwise reduction with B/H_0 held constant at 0.74 and H_0/H set at the same 1.19. The effect of H_0/H was also studied for the case when the widthwise reduction ratio was increased to 1.19.

Table 2 Calculation of forging condition

No.	B/H_0	W_0/W	H_0/H
1	0.10	No apply	1.19
2	0.74	No apply	1.19
3	1.06	No apply	1.19
4	0.74	No apply	1.13
5	0.74	1.10	1.19
6	0.74	1.19	1.11

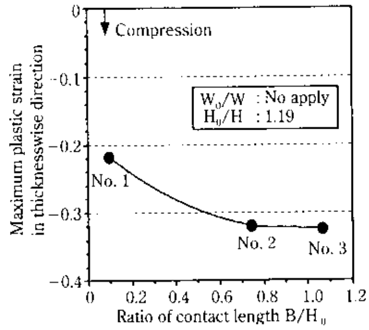

Fig. 2 Comparison of maximum plastic strain by simulation at the center of thickness

2.2 Results of Analysis and Discussion

Figure 2 shows the relationship between the maximum plastic strain in the thickness direction and the contact length ratio, B/H_0, when the thicknesswise reduction ratio is held constant. Although the amount of plastic strain increases as B/H_0 becomes larger, the effect of B/H_0 is slight above approximately 0.7. This result indicated that forging in the slab thicknesswise direction with a larger B/H_0 is effective in improving the internal properties of slabs in the reduction region. However, in actual manufacturing operations, it is necessary to apply a uniform forging effect over the full lenght of the slab, and there are limitations on the specifications of the forging equipment. In view of these facts, securing a large number of forging reduction passes in the lengthwise direction, with B/H_0 set at approximately 0.7, can be considered practical.

Next, regarding the effect of applying widthwise forg-

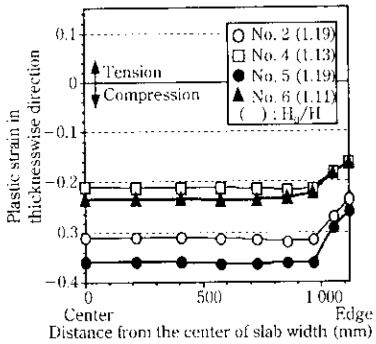

Fig. 3 Plastic strains by simulation in thicknesswise direction at the center of thickness (B/H_0 = 0.74)

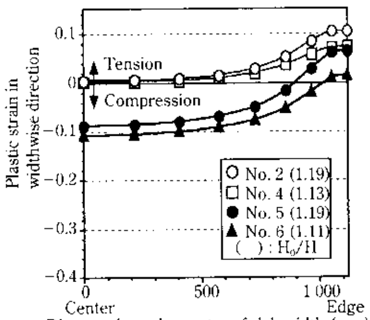

Fig. 4 Plastic strains by simulation in widthwise direction at the center of thickness (B/H_0 = 0.74)

ing reduction, **Figs. 3–5** show the results of a comparison of the plastic strain in the thickness, width, and lenght directions, respectively, at various points from the widthwise center of the slab to the edge, when B/H_0 was held constant at 0.74.

First, with regard to the amount of plastic strain in the thicknesswise direction in Fig. 3, a comparison of No. 2 and No. 5, which have the same H_0/H, shows a larger value for plastic strain with No. 5, in which widthwise reduction was performed prior to thicknesswise reduction. This result suggests that widthwise reduction is effective in improving internal properties because the slab thickness is increased to greater than the initial thickness, H_0, by the "dog bone" shape which is formed at the edges of the continuous casting slab by widthwise reduction, and this increases the effective reduction ratio in the subsequent thickness reduction process.

Figure 4 shows the plastic strain in the widthwise direction. In the case of No. 2 and No. 4, which received reduction only in the thicknesswise direction, strain was in the tension direction over the entire region of the slab, and the values were particularly large in the region from 1/4 of the slab width to the slab edge. In contrast, with No. 5 and No. 6, which received widthwise reduction, strain was in the compressive direction except in the

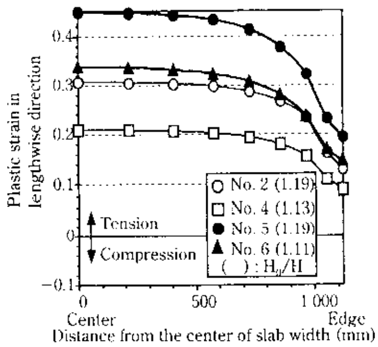

Fig. 5 Plastic strains by simulation in lengthwise direction at the center of thickness (B/H_0 = 0.74)

immediate vicinity of the widthwise edge. The compressive direction is the direction which closes porosities, and thus is effective in improving internal properties.

Figure 5 shows the plastic strain in the lengthwise direction, that is, the direction which the slab is elongated. Regarding the effect of applying (or not applying) widthwise reduction, comparing No. 2 and No. 5, which have the same H_0/H, and No. 4 and No. 6, in which different smaller values of H_0/H were used, the amount of plastic strain increased markedly in No. 5 and No. 6, which received widthwise reduction. This is thought to be the result of an increase in the metal flow in the lengthwise direction, proportionate to the decrease in widthwise volume due to reduction in the widthwise direction.

From the above, it is considered that the application of forging reduction in the widthwise direction imparts a larger compressive plastic strain in the thicknesswise and widthwise directions under conditions in which porosities have been enlarged and flattened in the lengthwise position, and therefore is an effective and reliable means of annihilating porosities in the center of thickness of continuous casting slabs.

3 Results of Factory Tests

Factory tests were conducted based on the results of the study of the annihilation of porosities in continuous casting slabs using elastic-plastic stress computer analysis. The plate manufacturing process is shown in **Fig. 6**; the specifications of the various facilities used are shown in **Table 3**. The items in this experiment were as follows.

(1) Confirmation of the porosity annihilation effect attributable to the forging reduction ratio in the slab thicknesswise direction
(2) Improvement of the porosity annihilation effect by application of forging reduction in the slab widthwise direction

3.1 Experimental Method

Using TS 400 MPa class steel having the chemical

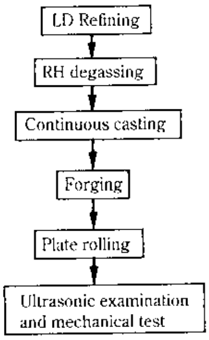

Fig. 6 Manufacturing process

Table 3 Specification of facilities

Continuous casting machine	Type: Vertical and bending Section of slab: 310 × 2 240 or 2 400 mm
Forging press	Type: Free hydraulic forging Capacity: Max. 7 200 t Anvil block: 800 × 3 800 mm Stroke: 3 000 mm
Plate rolling mill	Type: 4-Hi reversing Rolling force: Max. 8 000 t Work roll: ϕ1 220 × 5 490 mm

Table 4 Chemical composition

(mass%)

C	Si	Mn	P	S	Al
0.18	0.20	0.96	0.015	0.003	0.028

Table 5 Condition of forging and plate rolling (B/H_0: 0.74)

No.	Forging		Thickness of plates (mm)
	W_0/W	H_0/H	
A	No apply	1.07	220
B	No apply	1.13	220
C	No apply	1.19	220
D	1.10	1.19	220
E	1.19	1.11	240

Slab dimension (mm): 310 × 2 240 × 4 000
Heating temp. at forging (°C): 1 250
Heating temp. at plate rolling (°C): 1 150

composition shown in **Table 4**, plates with thicknesses of 220 mm and 240 mm were manufactured from continuous casting slabs 310 mm thick using a fixed B/H_0 value of 0.74 under the forging and plate rolling conditions shown in **Table 5**. With plates A-C, the forging reduction ratio was varied only in the thicknesswise direction to 1.07, 1.13, and 1.19, respectively, and the plates were rolled to a product thickness of 220 mm. Plate D was forged using a widthwise reduction ratio of 1.10 and a thicknesswise reduction ratio of 1.19, and was rolled to a thickness of 220 mm. Plate E was forged at an increased widthwise reduction ratio of 1.19 and a thicknesswise reduction ratio of 1.11, and was rolled to a thickness of 240 mm. The forging process was performed using one cycle of heating and forging with a heating temperature of 1 250°C. The plates were then manufactured by ordinary rolling at 1 150°C. To evaluate the internal properties of these heavy section steel plates, ultrasonic testing (UST), observation of the microstructure, and a thicknesswise tensile test were performed.

Table 6 Condition of UST

Probe	2Z30I
Sensitivity	V15-2.8: 50%
Frequency	2 MHz
Medium	Water
Surface condition	As roll

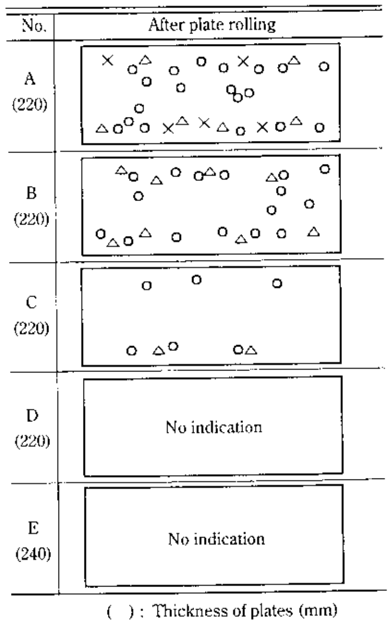

Fig. 7 Results of UST

3.2 Quality Properties of Steel Plates

Full surface slide flaw detection was performed under the UST conditions shown in **Table 6**. Here, the judgment standard for detection of defects was ○: 25% $< F_1 <$ 50%, △: 50% $< F_1 \leqq$ 100%, ×: $F_1 >$ 100%. The results of UST after rolling are shown in **Fig. 7**. Plates A-C, which received forging reduction only in the thicknesswise direction, showed a considerable number of remaining defects in the center of thickness, in a region approximately the same distance inward from the two edges as the initial thickness of the slab, along the lengthwise direction of the plate. The level of these defects improved remarkably with only a slight increase in the forging reduction ratio. The above-mentioned results are in agreement with the tendency that a larger

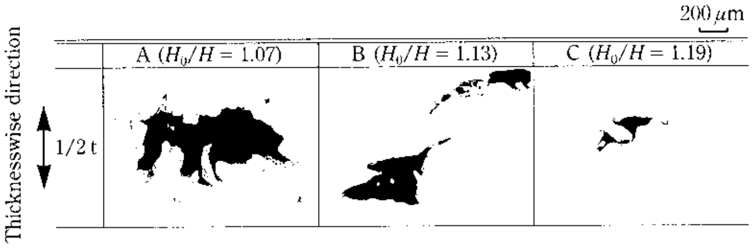

Photo 1 Micrographs of center porosities

Table 7 Results of tensile test

No.	Location	Direction	YP (MPa)	TS (MPa)	El (%)	RA (%)
A	1/2 t	Z	219	432	20	28
			217	426	19	27
			217	425	19	22
B			218	432	25	36
			216	430	20	29
			217	428	24	35
C			218	435	25	37
			215	439	21	30
			220	430	26	40
D			220	432	26	42
			217	436	27	45
			218	438	32	49
E			220	425	30	42
			217	429	26	39
			218	431	28	40

amount of plastic strain can be obtained when the value of H_0/H is increased, as was seen in the comparison of No. 2 and No. 4 in Fig. 3, where plastic strain in the thicknesswise direction was analyzed by varying the thicknesswise reduction ratio during forging.

In contrast to these results, plate D, received widthwise forging reduction, showed no defects at the same thickness of 220 mm. This result is attributed to the improvement of internal properties due to the change in widthwise plastic strain to the compressive direction and the greater plastic strain imparted in the thicknesswise and lengthwise directions, as shown in the comparison of No. 2 and No. 5 in Figs. 3–5, which compared the plastic strain in the thickness, width, and lenght directions due to performing (or not performing) widthwise reduction. Similarly, in the case of plate E, in which the widthwise forging reduction ratio was increased and the thicknesswise forging reduction ratio was decreased, a plate with no defects could be obtained. In manufacturing with actual equipment, buckling of the cross section during widthwise forging reduction was a concern, but under these conditions, with the W_0/W level of 1.19, manufacturing was possible with no problems.

Representative porosities taken from the defect areas detected by UST in plates A-C are shown in **Photo 1**. It can be seen that the size of the porosities decreases as the forging reduction ratio increases.

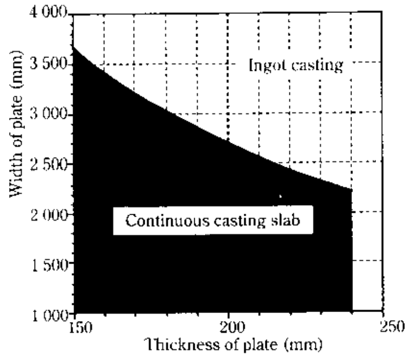

Fig. 8 Available plate size by application of alternative forging and plate rolling process or conventional process

Table 7 shows the results of tensile tests in the plate thicknesswise direction. As with the improvement in the UST results, a remarkable improvement in the reduction of area (RA) was observed.

The above-mentioned results confirmed that widthwise forging reduction is extremely effective in annihilating porosities.

4 Standardization of Forging Process for Heavy Section Steel Plates Using Continuous Casting Slabs

In the manufacture of steel plates with thicknesses of 220–240 mm, it was confirmed that sound heavy section plates can be manufactured by applying a bidirectional forging process in which reduction is applied in the slab thicknesswise direction after once performing reduction in the slab widthwise direction. Based on these results, Kawasaki Steel has adopted this method as a standard production process. **Figure 8** shows the applicable range (available size range) for manufacturing plates by the forging-plate rolling process using continuous casting slabs. It is possible to manufacture sound heavy section plates with thicknesses of up to 240 mm.

4.1 Soundness of Heavy Section Plates

In UST of plates manufactured by this process using the V15–2.8%: 50% flaw detection condition shown in Table 6, results showing no flaws were obtained. **Figure**

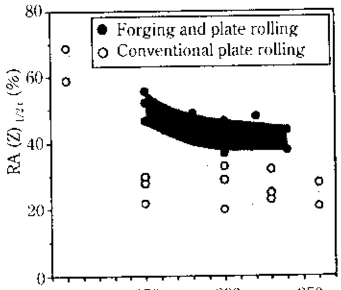

Fig. 9 Relation between thickness of plates and $RA(Z)_{1/2t}$

9 shows the results of a comparison of $RA(Z)_{1/2t}$ of tensile test pieces taken in plate thickness direction at the center of thickness with products from the new process and conventional continuous casting-plate rolling process. With the conventional process, $RA(Z)_{1/2t}$ shows a tendency to drop rapidly at thicknesses above 150 mm. In contrast, plates manufactured by the forging and plate rolling process show a high level of $RA(Z)_{1/2t}$.

5 Conclusion

In order to improve the internal properties of heavy section steel plates by annihilating the porosities found in continuous casting slabs, an effective forging method was studied using an elastic-plastic stress computer analysis, and factory tests were carried out. As a result, the following conclusions were obtained.

(1) Reduction of slabs in the thicknesswise direction with the ratio of the anvil block contact length and slab thickness, B/H_0, set at approximately 0.7 is effective in improving internal properties.

(2) Forging reduction in the widthwise direction is advantageous for improving internal properties because it generates widthwise plastic strain in the compressive direction and increases the effective thicknesswise reduction ratio by forming the slab edges into a "dog bone" shape.

(3) Larger widthwise reduction ratios are advantageous for improving internal properties; however, at the widthwise reduction ratio of 1.19 applied in this report, an adequate effect was realized with no problem of slab buckling.

(4) Application of this process made it possible to obtain extremely good internal properties in the manufacture of heavy section steel plates with a product thickness of 240 mm from 310 mm thick continuous casting slabs.

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