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Production of High Quality Extra Heavy Plates with New Casting Equipment

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Abstract

New casting equipment has been established in Nippon Steel Corp. Nagoya Works since 1996 which has the advantages of both ingot casting and continuous casting. This equipment has three characteristics. 1. The thickness of cast slabs is generally changeable from 245mm to 400mm (maximum 600mm); 2. The manufactured slabs are high quality for reduced nonmetallic inclusion and segregation with vertical casting and control of solidification; and 3. This equipment is capable of manufacturing high quality extra heavy plates for boiler and pressure vessels, mobile off-shore structures and other heavy duty structures, like the continuous casting process is capable of producing. With this process, the maximum plate thickness is 200mm for high quality extra heavy steel plates and 330mm for general, mild extra heavy steel plates. In this report, the authors describe this new casting equipment and provide examples of manufacturing results using extra heavy plates.

1. Introduction

Slabs which are press milled materials of steel plates can be separated into the two groups: Blooming slabs that are manufactured using the ingot casting method; and cast slabs that are manufactured using the continuous casting method. Normally, the ingot casting method is used to ensure stability and good quality of the mechanical properties in the thickness direction for high-quality extra heavy steel plates for use in boilers that exceed thicknesses of 100 mm. High pressure rolling or forging are the methods used for manufacturing.

Solidification takes time by allowing natural solidification through cooling in the atmosphere when using the ingot cast manufacturing method. Furthermore, it is necessary to apply ingot roll milling for those slabs, which increases the number of processes until a slab is manufactured. Additionally, it is unavoidable that shrinkage holes, minute air gaps, V segregation and reverse V segregation occur because of the natural solidification process, which mal-affect the quality of extra heavy steel plates. For that reason, thorough ratio of reduction have been applied using large steel ingots as well as the application of high shape factor roll milling technology for extra heavy steel plates.

On the other hand, the continuous casting method is primarily used for the manufacturing of steel materials from thin sheets to general steel thicknesses and high tensile strength steel. It is preferable from the viewpoint of shortened manufacturing to apply this continuous casting method to the manufacturing of extra heavy steel plates. However, because the casting section is then applied with the conventional continuous casting method, and the effect of the micro-porosity in the central segregation and final solidification of the

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central slab thickness, it has been difficult to apply this method to high-quality extra heavy steel plates.

In 1996, at the Nippon Steel Corporation Nagoya Works, ShinNittetsu developed new casting equipment that can be applied to extra heavy steel plates. This method incorporates the benefits of the ingot casting method and the continuous casting method that were mentioned above. This has been introduced and is being used to promote manufacturing of high-quality extra heavy steel plates. This paper describes the features of this new casting equipment and reports on the quality of extra heavy steel plates that have been manufactured using this equipment.

2. Quality Required for Extra Heavy Steel Plates

There are many types of phenomenon that can affect extra heavy steel plates that were not issues with plates having normal thicknesses, because of the larger thickness of such steel plates. This is related to 1) the mechanical properties of the plate in the thickness direction as is mentioned above. V segregation of steel ingots, reverse V segregation, and central segregation of continuous casting steel slabs affect the hardness and the toughness according to the degree of concentration of those components. On the other hand, with regard to 2) minute air gaps (cuttings, and micro-porosity), depending on the ratio of reduction, these affect the inner quality of the steel plates.

The variation of the mechanical properties and the inner quality of steel plates in the thickness direction that result from these, lead to problems regarding the performance of extra heavy steel plates as important members of the steel plates used in boilers. Therefore, in general, manufacturing is performed from ingot slabs for which there is a thorough pressure ratio. Quality modifications using special roll milling or forging are dually applied.

3. Features of Each Type of Slab Manufacturing Method

3.1 Ingot casting method (IC method)

The ingot casting method (IC method) is used to solidify molten steel by natural cooling after infusing it into a mold. The following outlines the three features of this method.

Initially, one advantage is the floating characteristic of nonmetallic inclusion caused by the slow speed of the solidification. The solidification of steel ingots takes a long time. In some cases, if the ingot is large, cooling can sometimes require as much as two days. During that time, large nonmetallic inclusion that exists in the molten steel rises to the surface and accumulates in the top portion of the steel ingot. The top portion of the steel ingot can then be cut away from the final product at the slab stage. The floating nonmetallic inclusion that has arisen is eliminated thereby making it possible to manufacture highly refined steel plates. The second advantage is that it is possible to manufacture freely for a multitude of size orders or small-lot orders. This is achieved by separate manufacturing for slabs sizes using steel ingot sizes, quantities, and ingot roll milling. The steel ingot manufacturing method is advantageous for small lot orders for extra heavy steel plates.

One of the demerits of this method of manufacturing is that it has a low level of productivity. A long period of time is required in this process from completing the infusion of the steel ingot until it has completely solidified. Furthermore, processes are included, such as heating the steel ingot and roll milling to create a slab. Therefore, there are many processes that are involved to achieve the final slab product.

With regard to segregation, the speed of solidification is slow with the natural cooling process thereby causing segregation and reverse V segregation to occur. There have been various attempts to remedy that situation by designing and studying different types of molds. However, these phenomena cannot be avoided.

3.2 Continuous casting method (CC method)

The continuous casting method (CC method) was developed with the presumption of ensuring high productivity. The bend type (see **Fig. 1**) is the main type that is used. Molten steel is infused into a water cooled mold via a tandish. Then, while being forcefully cooled by this cooling water, the steel is continuously pulled out and is cut at predetermined lengths by a gas cutter to form slabs. First, an ad-

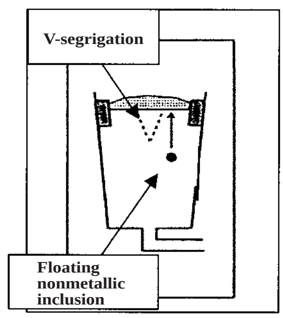
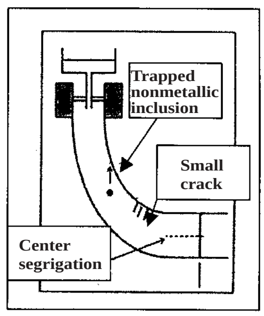
		Ingot casting	Continuous casting
Traditional casting process	Outline		
	Characteristics	○Advantage • Nonmetallic inclusion float easily • Applicable to many kinds of size • Applicable to small lot of order ○Disadvantage • Inefficient productivity	○Advantage • Efficient productivity (Accelerated cooling, omission of slabbing process) ○Disadvantage • Trapping inclusion • Center segregation • Almost constant size of slab • Not applicable to small lot of order

Fig. 1 Comparison of characteristics between ingot casting and continuous casting

vantage of this method is that inclusion occurs by this forced cooling. In comparison to the IC method, the casting speed is faster, and because ingot casting is unnecessary, there are fewer processes involved. A second advantage to this method is that it is possible for continuous casting to occur between molten steel charges. This method is highly productive.

A disadvantage, however, is that the thickness of the casting process is constant, therefore there is a limit to the thickness of the steel plates when manufacturing extra heavy steel plates. This reduces the ability to handle various sizes which in turn reduces the ability to support small lot orders because the minimum necessary volume of steel to be melted is large.

The following two points can be raised with regard to the disadvantages, in terms of quality. The first one is that there is centralized segregation. Solidification does occur by the forced cooling using cooling water in the continuous casting method. However, the final solidified portion is located in the center of the steel plate and the chemical components are concentrated in the molten steel making it easier for them to move through the process causing centralized segregation to be formed. This centralized segregation remains in the central portion of the steel plates and affects the mechanical properties of steel plates in the thickness direction of high-quality extra heavy steel plates that are to be used in applications requiring strict observance of quality standards, and affect the mechanical properties of welding joints. A second disadvantage is the nonmetallic inclusion. Nonmetallic inclusion floats part-way through the solidifying of the molten steel when using the bent type continuous casting method. However, there is a strong tendency for inclusion to become trapped in the solidified it shell portion that is equivalent to the casting surface. This causes many cases in which nonmetallic inclusion remains in the steel plates after roll milling. Note that there are modifying means using support equipment for the centralized segregation and nonmetallic inclusion. On the one hand, centralized segregation is also the final solidified portion. Naturally, fine porosity remains, which can affect the ability to ensure the inner quality of the extra heavy steel plates.

These have described the advantages and disadvantages of both the ingot casting method and the continuous casting method. Fig. 1 is a conceptual view of the features of the conventional casting method. In order to manufacture high-quality extra heavy steel plates with higher productivity, ShinNittetsu developed new casting equipment that combines the advantages of both the IC and the CC methods. This equipment was set up at the Nippon Steel Corporation Nagoya Works in 1996 and began operations.

4. Features of New Casting Equipment

The concept of this newly developed casting equipment was to attain a high quality to support orders for multi size and small lots with higher productivity. The points were to: 1) Have a good ability to support sizes with high productivity; and 2) Produce steel that is better or has an equivalent quality to that of the IC method.

4.1 Ability to support multiple sizes through high productivity

In order to ensure high productivity, cast manufacturing using the continuous casting type is preferable. However, it has been difficult to support small lot orders using the conventional bent type casting method, and to cast extra heavy steel for extra heavy steel plate materials. Thus, the casting apparatus was changed to a vertical type. Furthermore, the length of the continuous casting machine was set to 9.1 m to enable an extremely compact configuration.

The size of the steel slabs vary for the normal casting thicknesses from 245 to 400 mm (maximum 600 mm) and the width of the casting was set at 900 to 2,360 mm. This enables manufacturing of extra heavy steel plates of a maximum thickness of 200 mm presuming ratio of reduction of 2.

4.2 Steel quality equivalent or higher than the IC method

The two points relating to steel slab quality are inclusion and segregation.

tinuous casting type, it was configured to be a vertical type to enable it to support small-lot orders. In this way, it was possible to avoid the trap to the solidifying shell of the nonmetallic inclusion material that floats and was a problem when using the conventional bent type continuous casting machines. By reducing the casting speed to be slower than the conventional bent type continuous casting machines, it was possible to remove the floating time of the nonmetallic inclusion.

With regard to the segregation, by controlling the solidified structure using casting temperature control and molten steel flow controls, the centralized segregation found in the metal slabs from the conventional CC method had been dramatically reduced. Along with that, it was possible to reduce the fine porosity found in the central portion of the steel slabs.

The quality thus modified is at the same level in the length direction for each steel slab because it uses the continuous casting method. Considering this uniformity, it can be said that the steel slab manufactured using this new testing equipment is of a higher quality than that produced using the IC method.

This has described the features of the new casting equipment. **Fig. 2** is a conceptual view of this casting equipment. **Table 1** com-

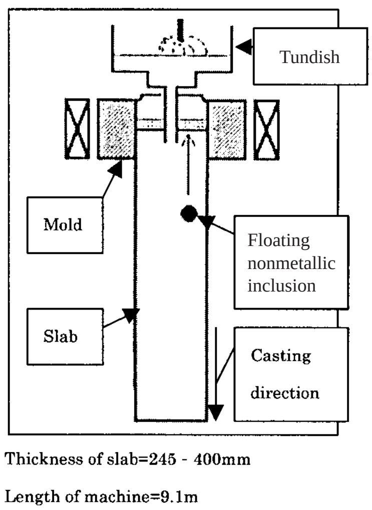


Fig. 2 Outline of new steel casting process

Table 1 Comparison of ordinary casting process and new steel casting process

Items	Ingot casting	Continuous casting	New steel casting process
Non-metallic inclusion	◎	△	◎
Segregation	○	○	◎
Applicable for size	◎	△	○
Applicable for lot	◎	×	◎
Productivity	×	◎	○

Note: The symbol means relative evaluation (poor ← ×, △, ○, ◎ → excellent).

pares the features of the conventional testing method with the new casting method.

5. Modification of Inner Quality of Extra Heavy Steel Plates Using Roll Milling

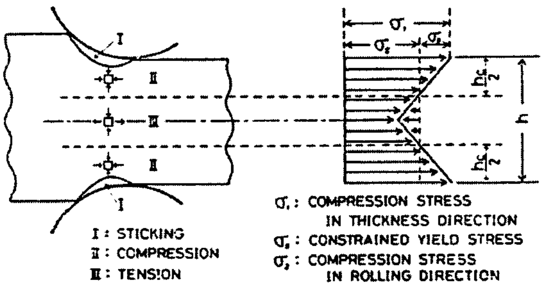
5.1 High shape factor roll milling method for crimping minute air gaps

There has been a great deal of research done with regard to the micro-porosity crimping technology for extra heavy steel plates[1]. These have been applied to extra heavy steel plate manufacturing as a high shape factor rolling method by ShinNittetsu. The general outline thereof is described below. **Fig. 3** shows the general outline of the distribution of strength in the thickness direction during rolling of extra heavy steel plates. The range of the compression stress region II widens near the center of the steel plate. The tensile stress region III is reduced, however it is necessary for micro-porosity crimping of the steel slab.

The roller and contact arc length of the profile of the materials, and the ratio of the average thickness of the material are called the shape factor. It is the technology of the high shape factor and compression technology to obtain a large shape factor. A shape factor of $1/h_m$ can be expressed[1] using the following equation (1).

$$1/h_m = \sqrt{(R(h_0 - h_1))/(\tfrac{1}{2}(h_0 + h_1))} \qquad (1)$$

In this equation, R is the diameter of a roller; h_0 is the thickness of the plate on the entrance to the roller; and h_1 is the thickness of the plate on the output side of this machine. **Fig. 4** shows the relationship of the shape factor and the compression stress region ratio (h_c/h) in the stress distribution when rolling. The shape factor is large while the compressions stress region increases in size near 1. The micro-



(a) Stress condition in roll gap (b) Distribution of compression stress in thickness direction

Fig. 3 Schematic drawings of stress distribution during rolling

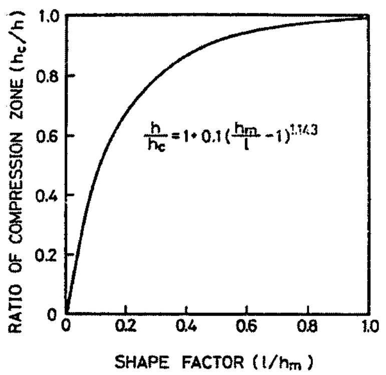


Fig. 4 Relations between shape factor and ratio of compression zone

Table 2 Pass schedule of plate rolling and shape factor (ex. thickness of slab is 400 mm)

Pass of rolling	Case A		Case B	
	Thickness	Shape factor	Thickness	Shape factor
	360		370	
1	340	0.31	350	0.30
2	310	0.41	320	0.40
3	280	0.45	290	0.44
4	250	0.51	260	0.49
5*	220	0.57	220	0.65

* Final thickness of rough mill

porosity is easily crimped.

To increase the shape factor, it is preferable to increase the roller diameter or to increase the compression amount ($h_0 - h_1$), which is understood from the equation (1).

5.2 Rolling extra heavy steel plates from the new type casting method

The Nippon Steel Corporation Nagoya Works has 2- rough finish stand mills and can apply a 20 mm finish for a 200 mm extra heavy steel plate and the send the now 220 mm steel plate from the rough roll milling machine to a finish roll milling machine.

At the rough roll milling machine, high compression rolling is applied in the rough final pass to produce the high shape factor rolling that is described above. **Table 2** is an example of the compression pass schedule and the shape factor. As can be seen in Fig. 4, when the shape factor exceeds 0.5, the compression stress region inside the steel plate reaches 90%. It can be said that the compression has thoroughly permeated the inside portion of the steel plate.

6. Example of the Scope of the Possible Extra Heavy Steel Manufacturing Using Slabs Manufactured by the New Casting Method

As described above, by combining the high shape factor rolling technology for improved quality of the inside a steel plates, with the extract heavy steel slabs manufactured using the new casting method, it is possible to manufacture high-quality extra heavy steel plates with a shorter manufacturing time than that of the conventional ingot casting method for extra heavy steel plates.

On the other hand, with regard to the type of steel (generally 40K extra heavy steel plates) for which good quality is strictly required for the inner portion of the steel plates, high shape factor rolling is not required. Also, by reducing the ratio of reduction from the slab to the steel plate, it is possible to shorten the manufacturing time of ultra extra heavy steel plates.

Fig. 5-1 Manufacturing size ability of normalized or normalized and tempered plate for boiler and pressure vessel

(mm)

Width of plate	1 600	2 200	2 800	3 400	4 000	4 500
Thickness of plate						
50						
100						
150						
200						
250						
300						

Fig. 5-2 Manufacturing size ability of general use carbon steel plate including extra heavy plate (mild steel example JIS SS 400)

(mm)

Width of plate	1 600	2 200	2 800	3 400	4 000	4 500
Thickness of plate						
50						
100						
150						
200						
250						
300						
330						
350						
380						

Fig. 5 shows an example of the possible scope of steel plate manufacturing using the new casting method.

7. Example of Manufacturing Results Using the Actual Machines

7.1 Carbon steel plates for boilers

JIS SB 480 steel plates of 195 mm were manufactured as carbon steel plates for boilers using the high shape factor rolling from a 400 mm steel slab in the new casting method. **Fig. 6** shows the manufacturing processes. Said steel plates were manufactured with the premise of stress reliefing annealing (SR) being applied 4 times × 625°C × 3.45 h. Materials were designed to satisfy the rated standard values after said SR.

7.1.1 Results of the manufacturing

Table 3 shows the chemical compositions and actual maximum shape factors. **Table 4** also shows the mechanical test results.

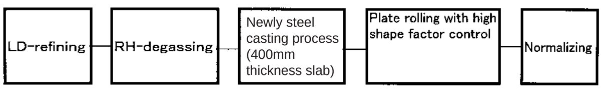


Fig. 6 Manufacturing process for extra heavy plate of SB 480

The results after performing tensile strength testing and Charpy impact testing on 1/4 t (t: plate thickness) and 1/2t, showed there was no major difference in the thickness positions and that these slabs had good characteristics. **Fig. 7** shows the hardness of distribution in the plate thickness direction. **Fig. 8** shows the microstructure

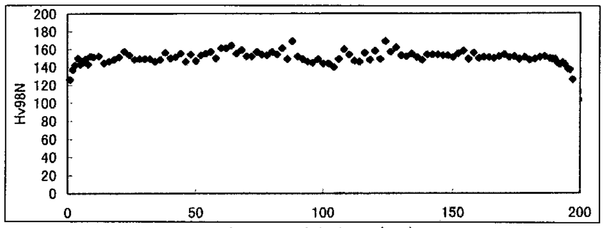


Fig. 7 Hardness distribution of through thickness

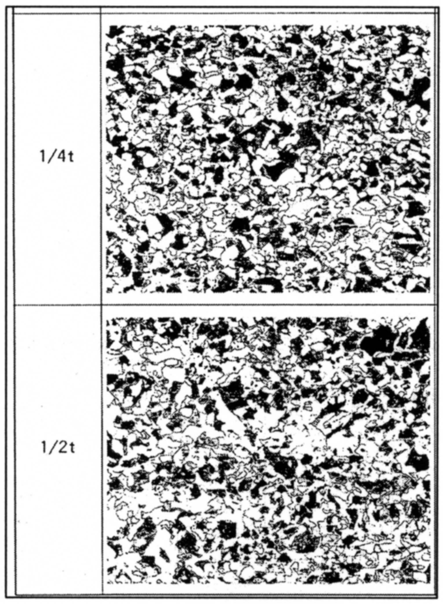


Fig. 8 Microstructure of SB 480 (× 100)

Table 3 Chemical compositions and maximum shape factor

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo
Actual value	0.27	0.23	1.11	0.012	0.004	0.16	0.20	0.15	0.09
Specification	≤ 0.30	0.13-0.33	≤ 1.15	≤ 0.035	≤ 0.035	–	–	–	–
Maximum shape factor		0.52							

Table 4 Mechanical properties of SB480 extra heavy plate

Items	Location of thickness	Test results			Test piece heat treatment
Tensile test	Specification	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)	SR: 625°C × 3.45h * 4 times
		≥ 265	480-620	≥ 18	
	1/4t	355	549	34	
	1/2t	354	544	32	
Charpy impact test (0 °C)		Min.(J)	Ave.(J)		
	1/4t	71	80		
	1/2t	49	70		

in the 1/4 t and the 1/2t. **Table 5** shows the results of the ultrasonic wave testing inspections (UST results) using JIS G 0801. It was verified that the extra heavy steel plates SB 480 that were manufactured using the new casting method had good quality.

7.2 Low allow Cr-Mo steel for pressure vessels

This shows the results of manufacturing ASTM A387-22-2 steel plates with a thickness of 130 mm as the low alloy Cr-Mo steel for pressure vessels. The steel was manufactured using 400 mm slab from the new casting method and high shape factor rolling. **Fig. 9** shows the manufacturing processes. The steel plate underwent normalizing and tempering for the rated standard heat treatments. However presuming SR680°C × 10.4 h, and considering low temperature toughness, accelerated cooling was performed after normalizing then the steel plate was tempered.

7.2.1 Results of the manufacturing

Table 6 shows the chemical components and maximum shape factor. **Table 7** shows the results of the mechanical tests. After evaluating the 1/4t and 1/2t, it was found that there were no large differences. Also, as shown in **Fig. 10**, for the hardness distribution in the plate thickness direction, no localized hardness by segregation was found.

7.3 Extra heavy HT780 steel plates

Extra heavy HT780 steel plates are used in offshore structures and for industrial machines. This shows the results of manufacturing

Table 5 Test result of UST

Specification of UST		UST result
JIS G 0801	Sensitivity V15-2.8: 50% Frequency: 2MHz Medium: Water	Acceptable

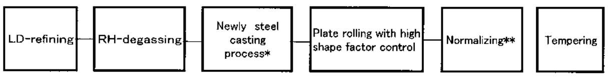
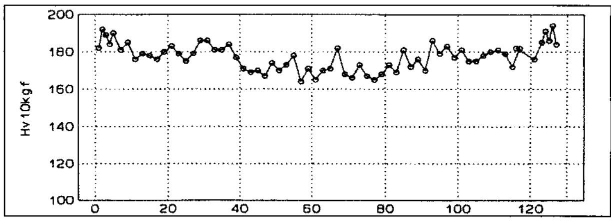


Fig. 9 Manufacturing process for extra heavy plate of A387-22-2
***400mm thickness slab, **Accelerate cooling**



Location of thickness (mm)

Fig. 10 Hardness distribution of through thickness

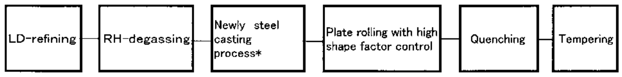


Fig. 11 Manufacturing process for extra heavy plate of HT780
***400mm thickness slab**

HT780 steel plates having a thickness of 178 mm on the actual machines using the new casting method. The steel slabs used were 400 mm. High shape factor rolling was performed. **Fig. 11** shows the manufacturing processes.

7.3.1 Results of the manufacturing

Table 8 shows the chemical components and maximum shape factor. **Table 9** shows the mechanical characteristics. To manufacture extra heavy HT780 steel of 178 mm, quenching and tempering are used. However the cooling speed for 1/2t is lower than that for 1/4t, therefore the cooling rate for quenching 1/2t is that much lower and the strength decreases. However, the HT780 steel has good characteristics. **Figs. 12** and **13** show the microstructures and the macrostructures. There was no large difference found in the plate thickness direction. The results of running UST on JIS G 0801 showed that these slabs passed.

7.4 Extra heavy general 40 K steel plates

The results of the manufacturing described above showed that it supports various types of usages that have strict standards. This creates good inner quality using the high shape factor rolling method. On the other hand, as described in section 6., there is a great need in

Table 6 Chemical compositions and maximum shape factor of A387-22-2 extra heavy plate

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo
Actual value	0.14	0.14	0.54	0.007	0.002	0.03	0.03	2.20	0.97
Specification	0.05-0.15	≤ 0.50	0.30-0.60	≤ 0.035	≤ 0.035	–	–	2.00-2.50	0.90-1.10
Maximum shape factor	0.81								

Table 7 Mechanical properties of A387-22-2 extra heavy plate

Items	Location of thickness	Test results				Test piece heat treatment
Tensile test	Specification	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction area (%)	
		≥ 310	515-690	≥ 18	≥ 45	
	1/4t	455	591	31	76	SR: 680°C × 10.4h
Charpy impact test (– 40°C)	1/2t	439	573	30	76	
		Min. (J)	Ave. (J)			
	1/4t	195	210			
	1/2t	260	280			

Table 8 Chemical compositions and maximum shape factor of HT780 extra heavy plate

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V
Actual value	0.11	0.26	1.11	0.004	0.001	0.23	2.47	0.56	0.53	0.04
Maximum shape factor	0.63									

Table 9 Mechanical properties of HT780 extra heavy plate

Items	Location of thickness	Test results				Test piece heat treatment
Tensile test	Specification	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction area (%)	Non
		≥ 690	793-965	≥ 15	–	
	1/4t	871	930	23	68	
	1/2t	795	873	20	51	
Charpy impact test (–27°C)		Min. (J)	Ave. (J)			
	1/4t	142	152			
	1/2t	57	67			

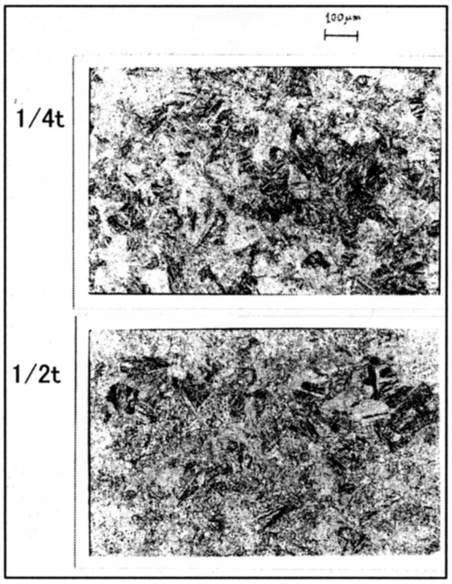


Fig. 12 Microstructure of HT780 extra heavy plate

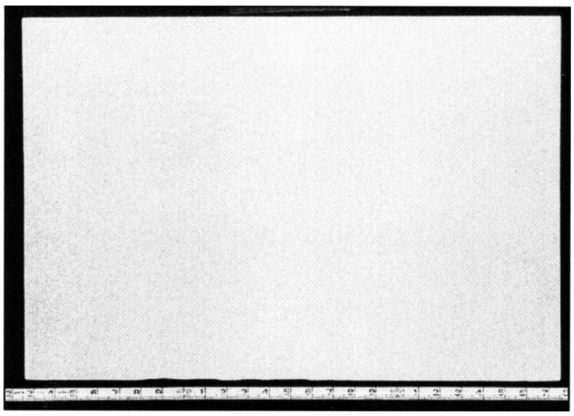


Fig. 13 Macrostructure of HT780 extra heavy plate

the market for ultra heavy 40K steel plates that are mill manufactured having no strict standard requirements for the inner quality. This shows the results of manufacturing ultra heavy 40 K steel plates SS 400 having a thickness of 350 mm manufactured using the new casting method.

The steel slabs used were 400 mm and the steel plates of 350 mm were manufactured by rolling. **Fig. 14** shows the manufacturing processes.

7.4.1 Results of the manufacturing

Table 10 shows the chemical components. **Table 11** shows the mechanical characteristics. While rolling was used as is, the SS 400 standards were satisfied. Also, in the Charpy impact tests executed

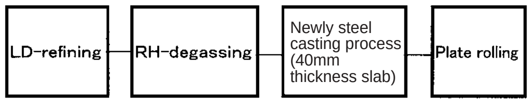


Fig. 14 Manufacturing process for extra heavy plate of SS 400

Table 10 Chemical compositions of extra heavy plate of SS 400

	C	Si	Mn	P	S
Actual value	0.17	0.24	1.07	0.013	0.005
Specification	–	–	–	≤ 0.050	≤ 0.050

Table 11 Mechanical properties of SS 400 extra heavy plate

Items	Location of thickness	Test results		
Tensile test	Specification	Yield point (MPa)	Tensile strength (MPa)	Elongation (%)
		≥ 215	400-510	≥ 23
	1/4t	240	448	25
	1/2t	222	426	24
Charpy impact test (0°C)		Min. (J)	Ave. (J)	
	1/4t	21	32	
	1/2t	12	15	

for reference, it was verified that there was a impact value of the average 30J level at 0°C.

The above describes the results of the manufacturing using a new casting method for various types of extra heavy steel plates. In view of these results, it is understood that it is possible to attain high quality using the new casting method.

8. Conclusions

This paper describes the features of the new casting method set up at the Nippon Steel Corporation Nagoya Works, and the characteristics of high-quality extra heavy steel plates manufactured using that combined with the high shape factor rolling technology. The following outlines the conclusions found.

(1) While the new casting method employs the continuous casting method, it has higher productivity than ingot casting that had been used conventionally to manufacture extra heavy steel plates. Furthermore, an equivalent or higher quality to that of ingot casting was ensured for the inner quality of the steel plates with regard to segregation and nonmetallic inclusion.

(2) Using the ultra heavy steel plate manufacturing processes of the new types of casting method (slab thickness of 400 mm) and the high shape factor and compression, it was possible to manufacture steel plates using the continuous casting method up to plate thicknesses of 200 mm for steel plates for boiler and pressure vessel use, and high-quality extra heavy steel plates with high tensile strengths.

(3) It is possible to maintain stable manufacturing of 400 MPa class, 330 mm ultra heavy steel plates for which plate thickness and strength are important.

With ASTM 2002 A20/A20M, as a condition to alleviate the ratio of reduction compression ratio of the manufacturing of steel plates from 3 to 2, the various testing technologies and rolling conditions were prescribed. Combining the new casting method with the high shape factor, these were all satisfied.

It is necessary to convert from the conventional processes for the steel manufacturing processes in view of the global environment problems and energy problems.

There is an extremely high demand for extra heavy steel plates. Converting from the conventional ingot casting method to the new casting process will open up a whole new world for extra heavy steel plates which provides us with great expectations for the future.

References

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