Characteristics of Stainless Steel Strip Cast

by Twin Rolls*

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Synopsis

Experiments on the strip casting of a Type 304 stainless steel have been done by the use of a twin-roll caster with the copper alloy rolls of 400 mm diameter and 300 mm wide. Cast strips of 120 kg with good shape and appearance were obtained with high reproducibility. The casting speed was 17~40 m/min, and the length and thickness of the strip were about 30 m and 0.8~2.3 mm, respectively. At an early stage of the casting operation the thickness reduces rapidly, and then approaches a constant value. According to the analysis of heat transfer and thermal expansion of rolls, the early decrease in thickness seems to be caused by the thermal expansion of rolls. The cast strip is not free from defects which should be minimized. The microstructure and segregation of the cast strip have also been investigated. The tensile properties of the cold rolled sheets by this process satisfy those as a Type 304 stainless steel.

Key words: continuous casting; twin-roll caster; strip casting; stainless steel; tensile property.

I. Introduction

It is generally accepted that the manufacturing processes of stainless steel have nearly been established. To effect a further reduction of the production cost, drastic technical innovations are desired in the processes. The strip casting is one of the techniques which have come to be paid attention to under the above background. Especially, stainless steel is considered to be a material suitable for the strip casting compared with plain carbon steel, because of small outputs and minor amounts of scaling. The strip casting has, of course, the merit of bringing the cost down owing to the elimination of hot rolling. In addition, reasonable expectations are entertained for the direct shaping of materials difficult to hot work and the improvement of strip properties by rapid solidification.

Although the strip casting of steel has been tried more than once in the former times, especially lately extensive investigations related to single-roll¹⁾ and twin-roll²⁻⁵⁾ processes have been made. However, it seems to have not reached the stage for practical use yet. From the reason that the twin-roll process has

excellent formability of strip, the authors commenced a study which aimed at prospecting the industrial possibility of this process. The present report provides the characteristics of Type 304 stainless steel strips cast by the prototype twin-roll machine.

II. Casting Procedure

Casting tests of Type 304 stainless steel strips were done by the use of a twin-roll caster with the internally water-cooled copper alloy rolls of 400 mm diameter and 300 mm wide. Steel of 120 kg was melted in a high frequency induction furnace and poured into a casting tundish. When the superheat of the melt in the tundish reached about 50°C, casting was started. The meniscus level in the caster was controlled with the aid of an inspection TV camera. The casting speed was 17~40 m/min, and the length and the thickness of the strip were about 30 m and 0.8~2.3 mm, respectively.

III. Results and Discussion

1. Appearance of Strip

The typical appearance of the cast strip is shown in Fig. 1. Cast strips with good shape and appearance were obtained with high reproducibility. The strip occasionally has surface defects such as cracks, folds and scums. The surface cracks can be classified into two main groups. One occurs on the casting rolls, and the other in the secondary cooling zone. The number of surface cracks was able to decrease to about one fifth by keeping the roll separating force below a certain value. The roll separating force during casting was measured by load cells and adjusted on the basis of the measured values. Moreover, porosity was infrequently observed in the middle of plate thickness of a strip at the position where the cooling was locally inadequate. A typical porosity observed by SEM is shown in Fig. 2. From this figure, a porosity is evident to be a shrinkage cavity.

Fig. 1. Appearance of cast strip.

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Fig. 2. Typical SEM photograph showing the inside of porosity.

2. Longitudinal Variation in Thickness

The variation in thickness along the length of a strip is illustrated in Fig. 3, where the data are the average of five measurements in the middle part of the strip width. At an early stage of casting operation, the considerable decrease in thickness was observed. This is considered to result from thermal expansion of rolls, as mentioned below. If first 6 m of the strip and then the tendency of the low-pitched decrease in thickness with strip length are excluded, the longitudinal variation in thickness seems to be within about ± 0.05 mm.

Temperature distribution in the radial direction of a roll sleeve was calculated on the basis of a linear non-steady-state heat-transfer model, in order to estimate the decrease in thickness along the length of a strip owing to the thermal expansion of rolls. The boundary condition when the roll surface touches the metal pool is termed “the boundary condition (i)” and that when the roll surface is exposed to the air “the boundary condition (ii).” Under the boundary condition (i) the three media of melt (solidified shell) / roll sleeve / cooling water are taken into account, and the temperatures of the melt at less than 20 mm’s distance from the melt–roll sleeve interface and the roll sleeve were calculated. The value of $0.28 \text{ cal/cm}^2\cdot\text{s}\cdot^\circ\text{C}$ was used as a heat-transfer coefficient in the roll sleeve–cooling water interface. The temperatures of the cooling water and the melt bulk more than 20 mm apart from the melt–roll sleeve interface were assumed to have constant values of 20 and $1\,500^\circ\text{C}$, respectively. It is presumed that the melt and the solidified shell are a uniform medium and there exists no interface between the two, and the part whose temperature is lower than that ($1\,435^\circ\text{C}$) when the solid fraction is 0.35 is regarded as a solidified shell. Under the boundary condition (ii) the three media of air/roll sleeve/cooling water were brought into consideration, and only the temperature of the roll sleeve was computed. The heat is assumed to be removed

Fig. 3. Variation in thickness along the length of a strip.

Table 1. Values used for calculations.

Thermal conductivity, k (cal/cm·s·°C)	Cu alloy	$0 \leq T < 300^\circ\text{C}$ $k = 1.30 \times 10^{-4}T + 8.32 \times 10^{-1}$
	Type 304 ⁽⁶⁾	$0 \leq T < 800^\circ\text{C}$ $k = 3.56 \times 10^{-5}T + 3.60 \times 10^{-2}$
		$800 \leq T < 1\,428^\circ\text{C}$ $k = 1.71 \times 10^{-5}T + 5.00 \times 10^{-2}$
		$T \geq 1\,428^\circ\text{C}$ $k = 7.44 \times 10^{-2}$
Specific heat, C (cal/g·°C)	Cu alloy	$C = 2.36 \times 10^{-5}T + 9.16 \times 10^{-2}$
	Type 304 ⁽⁶⁾	$C = 3.25 \times 10^{-5}T + 1.25 \times 10^{-1}$
Coefficient of linear expansion ($^\circ\text{C}^{-1}$)	Cu alloy	1.8×10^{-5}
Poisson's ratio	Cu alloy	0.37

by radiation in the air–roll sleeve interface. The value of 0.79 was used as an emissivity, and the air temperature was supposed to have a constant value of 20°C . Under the initial condition that the temperatures of the melt and roll sleeve are $1\,500$ and 20°C , respectively, the calculation was made by changing the above two boundary conditions alternately at the periodic intervals which were determined by the roll revolution rate and the height of the metal pool. Every time the roll surface begins to touch the metal pool, the melt temperature is set equal to $1\,500^\circ\text{C}$ but the roll sleeve succeeds to the temperature distribution just before. The values used for calculations are shown in Table 1. The calculated result was verified by measuring the roll surface temperatures at the position 180° from the narrowest roll gap with thermocouples. The value of $0.15 \text{ cal/cm}^2\cdot\text{s}\cdot^\circ\text{C}$ was adopted as a heat-transfer coefficient h in the melt (shell)–roll sleeve interface. The calculated value of the roll surface temperature approximately agreed with the data, as shown in Fig. 4. Figure 5 shows the calculated results of the changes in the surface and inside temperatures of the roll sleeve with time. As is evident in this figure, the temperature of the roll sleeve reaches a steady state in about 100 s.

On the basis of the calculated temperature distribution in the radial direction of a roll sleeve, the problem of thermal stress⁷⁾ for a cylinder was solved. On the assumption that the temperature is uniform in the circumferential and axial directions, the amounts of

thermal expansion of a roll sleeve in the radial direction are given by Eqs. (1) and (2) in the cases of constrained edges and free edges, respectively.

$$\Delta r = \frac{2(1+\nu)b\alpha}{(b^2-a^2)} \int_a^b [T(r)-T_0]rdr \dots\dots\dots(1)$$

$$\Delta r = \frac{(2-3\nu)b\alpha}{(1-\nu)(b^2-a^2)} \int_a^b [T(r)-T_0]rdr \dots\dots\dots(2)$$

where, Δr : amount of thermal expansion of a roll sleeve in the radial direction
 a : internal radius (160 mm)
 b : external radius (200 mm)
 α : linear expansion coefficient
 $T(r)$: temperature distribution of a roll sleeve in the radial direction
 T_0 : initial temperature of a roll sleeve (20°C)
 ν : Poisson's ratio.

With $T(r)$ obtained from the above computation, the values 0.96 and 0.50 mm of $2\Delta r$ were calculated from Eqs. (1) and (2), respectively. The values used for this calculation are also shown in Table 1. The calculated values of $2\Delta r$ are in substantial agreement with the decrease in thickness shown in Fig. 3. From the above consideration, the decrease in thickness along the length of a strip was considered to be caused predominantly by thermal expansion of roll sleeves. Consequently the thickness of a strip may become

Location: 180° from the narrowest roll gap

Fig. 4. Comparison of roll surface temperature between the data and the calculated value.

Fig. 5. Calculated results of changes in roll sleeve temperatures with time.

constant, after the temperature of roll sleeves reached the steady state.

3. Solidification Rate

Since the solidification rate in the twin-roll process is not so easy to determine due to the thickness reduction by casting rolls and is not well-known, an additional experiment has been done to evaluate it by a dip test. The procedure of this test was described previously⁸⁾ and hence is omitted in this paper. As the result is shown in Fig. 6, the solidification rate is able to express by the $\sqrt{t}$ rule even in the short cooling time of 0.4~2.1 s. The value of the solidification constant in the case of a cooling block with a cylindrical surface is 2.66 mm/s^{1/2}. This value seems to agree with that corresponding to a solidification constant in the twin-roll caster. The result of the heat-transfer analysis of the melt and roll sleeve as mentioned above is shown in Fig. 6, where the data of a solidification constant in the dip test is also in good agreement with the calculated result. However, it should be noted that the constant term in the solidification rate equation varies according to the experimental apparatus.

4. Microstructure of Strip

Although the microstructures differ somewhat among the different samples, generally the columnar dendrite without and then with secondary arms appear successively from the surface to the inside as shown in Fig. 7(a). Furthermore, the structures in the middle of the thickness can be classified into the following two main cases;

- (i) The equiaxed crystal is located.
- (ii) The columnar dendrite grows to the finally solidified position.

In the former, the columnar dendrites outside the equiaxed zone is often replaced by the branched columnar dendrites. The columnar dendrites located outside the equiaxed zone is frequently inclined to the casting direction, as shown in Fig. 7(b). This is considered to be due to the fact that the liquid metal in front of the shell in the metal pool has the relative

Fig. 6. Solidification rates of Type 304 melt measured by a dip test and calculated for the twin-roll process.

velocity opposite to the casting direction. In the latter, it is often observed that the tips of the dendrites bend oppositely to the casting direction, as shown in Fig. 7(c). This reason is presumed to be that the high temperature part of the shells is forced to flow owing to the reduction of a strip by the rolls in the roll gap. However, it is difficult to know the cast structure exactly, since the middle part of the thickness has already recrystallized in the as-cast state occasionally.

The strip cast by the twin-roll technique exhibits the characteristic white color in the middle part of the thickness upon being etched, as shown in Fig. 7(c) (the part is referred to as the white zone). The white zone may be formed by the phenomenon that concentrated solutes are squeezed out⁴⁾ when two shells encounter and a strip begins to be reduced by two rolls. In the case that the equiaxed zone exists in the

middle part of the thickness as shown in Fig. 7(b), the white zone is not so clear but undoubtedly present. In this sample, the white zone is thicker than the equiaxed zone, and includes the tips of the columnar dendrites. The negative segregation in the white zone was investigated by EPMA line analysis in the direction of thickness. Although C, Si, Mn, P, S, Ni, and Cr were analyzed, very slight negative segregations are observed with respect to only C, Mn and Ni, as shown in Fig. 8.

Figure 9 shows the δ -ferrite distribution along the thickness of the as-cast strip. A good deal of δ -ferrite remains in the subsurface layer. The amount of δ -ferrite measured by a ferrite magnetometer varies from 0.5 to 6 %, but is able to be decreased by cold rolling and annealing to the same level as that of the conventional material.

In order to estimate the cooling rate of the strip, the secondary dendrite arm spacing d_2 was measured, and the result was plotted against the distance from the chill surface and is shown in Fig. 10. The data show the average of many measurements in several dendrites. The values of d_2 in this study are 2~6 μm , but those in the subsurface layer of the conventional CC slab of 150 mm thickness are 10~14 μm . The cooling rate of the present strip was estimated from Sugiyama *et al.*'s data⁹⁾ (the cooling rate=0.2~2.0°C/s) for d_2 of Type 304 stainless steel, assuming that d_2 is inversely proportional¹⁰⁾ to the third root of the cooling rate. As a result, the cooling rate of the strip is estimated to be $10^3\sim10^4$ °C/s as illustrated in

Longitudinal cross section
(a) Subsurface layer
(b), (c) Middle part of thickness
Fig. 7. Microstructure of the cast strip.

Fig. 8. EPMA line analysis in the thickness direction of the white zone.

Fig. 9. Distribution of δ -ferrite along the thickness of the as-cast strip.

Table 2. Chemical composition of the strip cast material. (wt%)

	C	Si	Mn	P	S	Ni	Cr	N
Type 304	0.053	0.55	1.07	0.024	0.005	8.35	19.02	0.013

Table 3. Tensile properties of the Type 304 strip cast material at room temperature.

Condition	Specimen	Thickness (mm)	0.2 % Y.S. (kg/mm ²)	T.S. (kg/mm ²)	Elongation (%)
As cast+Anneal* ¹ +60 % CR* ² +Anneal* ³	Long.	0.60	27.9	70.2	53.0
	Trans.	0.60	27.3	68.1	54.0
As cast+Anneal* ¹ +60 % CR+Anneal* ³ +50 % CR+Anneal* ³	L	0.30	27.8	72.0	54.5
	T	0.30	27.5	69.5	54.9
Conventionally produced Type 304	T	0.60	28.0	70.0	60.5

*¹ 1 100°C×60 s *² CR=Cold rolled *³ Cooled immediately after attaining to 1 050°C.

Fig. 10. Secondary arm spacing and cooling rate of the cast strip.

Fig. 10, and is one order larger than that of the conventional slab.

5. Mechanical Properties of Cold Rolled Sheets

After the as-cast strip was annealed and pickled without surface treatments and cold rolled without or with the intermediate annealing, tensile tests were done. The chemical composition of the cast strip is shown in Table 2. The cold rolling condition and the tensile properties of the sheets by this process are shown in Table 3, compared with the average of conventionally produced Type 304 stainless steel sheets. The yield and tensile strengths of the sheets by this process are essentially the same as the conventionally produced sheets, but the elongation is somewhat lower than that of the conventionally produced material. However, the tensile properties of the cold rolled sheets by this process satisfy those as a Type 304 stainless steel.

IV. Conclusion

Experiments on the strip casting of a Type 304 stainless steel have been done by the use of the prototype twin-roll caster. Cast strips of 120 kg with good shape and appearance were obtained with high reproducibility. The tensile properties of the cold rolled sheets by this process satisfy those as a Type 304 stainless steel. By decreasing the defects of the as-cast strip further, the quality of the strip by this process is expected to improve to that of the conventionally produced strip hereafter.

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