Abridged version

KAWASAKI STEEL TECHNICAL REPORT
No.32 (March 1995)
Ironmaking Technology, Secondary Refining,
and Center-Segregation Control with Forging in CC

Concept of Continuous Forging Process and Experimental Analysis of Forged Blooms

Shinji Kojima, Hisakazu Mizota, Koichi Kushida

Synopsis :
With a view to substantially improving centerline segregation, the authors developed the continuous forging process, based on a completely new solidification mechanism. In the new method, the unsolidified bloom is subjected to heavy reduction at the stage of final solidification by anvils installed in the strand line. The effectiveness of the method has been confirmed using commercial continuous bloom casters, where it was found that centerline segregation can be eliminated and the segregation ratio of carbon C/C0 can be controlled to an aimed value between 0.6 and 1.0 by choosing an appropriate ratio of reduction to the unsolidified thickness. It was also found that semi-macro segregation can be reduced and internal quality is quite stable in spite of deviations in casting conditions during actual operation.

The body can be viewed from the next page.

KAWASAKI STEEL TECHNICAL REPORT No. 32 March 1995

Concept of Continuous Forging Process and Experimental Analysis of Forged Blooms*



Shinji Kojima
General Manager, Technology Dept., Kawaden Co., Ltd. (Former General Manager, Process Technology Dept., Steel Technology Div.)

Hisakazu Mizota
Staff Deputy Manager, Development & Design Sec., Process Development Dept., Mizushima Works

Koichi Kushida
Staff Assistant Manager, Steelmaking Sec. II, Steelmaking Dept., Mizushima Works

Synopsis:

With a view to substantially improving centerline segregation, the authors developed the continuous forging process, based on a completely new solidification mechanism. In the new method, the unsolidified bloom is subjected to heavy reduction at the stage of final solidification by anvils installed in the strand line. The effectiveness of the method has been confirmed using commercial continuous bloom casters, where it was found that centerline segregation can be eliminated and the segregation ratio of carbon C/C_0 can be controlled to an aimed value between 0.6 and 1.0 by choosing an appropriate ratio of reduction to the unsolidified thickness. It was also found that semi-macro segregation can be reduced and internal quality is quite stable in spite of deviations in casting conditions during actual operation.

1 Introduction

The quality levels required in steel products have become increasingly high in recent years. In continuously cast blooms and the majority of cast ingots, solidification proceeds by way of heat removal from the four peripheral faces. Centerline segregation accompanies the progress of solidification because solutes are expelled into the liquid phase at the solidus-liquidus interface (solidus line).[1] This tendency becomes more pronounced as the thickness of the bloom increases. In solidification during continuous casting, the length of the crater increases at higher casting speeds, encouraging centerline segregation.[2] The solute concentration of P and S is high in the area of centerline segregation; for this reason, the bloom center shows increased embrittlement, decreased workability, and other forms of deterioration, and bloom-center mechanical properties are reduced.

Historically, various methods have been proposed as means of alleviating centerline segregation in the continuous casting process. Methods applied to transform the solidified structure at final solidification from a columnar cristal to an equiaxed crystal include electromagnetic stirring,[3] low temperature casting,[4] wire addition,[5] ultrasonic power,[6] and others. Electromagnetic stirring is the most widely used of these methods, but changing the solidified structure alone is inadequate to prevent segregation. Another frequently reported method is soft reduction[7,8] to prevent enriched liquid steel from being drawn into the solidifying strand during final solidification by the contraction associated with solidification.

The continuous forging process[9] described here is a newly developed technology for continuous casting, and continuously applies mechanical energy at the stage of final solidification using a forging mechanism. The aim is to obtain a fine, segregation-free resolidified structure at the bloom center by the simultaneous expulsion of enriched molten steel and destruction of crystal grains during final solidification. This process can be considered a new solidification mechanism, which might be called forced-destructive solidification.

This paper describes the concept of the continuous forging process, the influence of casting and forging conditions on centerline segregation in commercial-scale forging experiments conducted to confirm the effects of the new process, and the improvement in bloom quality realized with continuous forging.

* Originally published in *Kawasaki Steel Giho*, **26**(1994)1, 1-6

2 Concept of Continuous Forging Process

2.1 Mechanism of Centerline Segregation in Continuous Casting

Steel includes C, Si, Mn, P, S, and other non-ferrous metal and nonmetallic components and demonstrates a wide range of properties depending on differences in the contents of these substances. During casting, these substances gradually accumulate as "enriched" molten steel in the molten steel remaining in the solidus-liquidus coexistence region. Because diffusion in the solid phase is slight, this enriched steel remains as centerline segregation after solidification.

In continuous casting, the crater becomes longer at higher casting speeds and the shape of the crater end assumes a sharper angle, which results in greater centerline segregation. This phenomenon is accelerated by bulging between the support rolls, and the degree of C segregation in the central area typically reaches 1.1 to 1.4.

2.2 Mechanism for Improvement of Centerline Segregation

Continuous forging is a technique by which enriched molten steel is forced out of the crater and dendrite is crushed by the application of mechanical energy at the final stage of solidification. The purpose of this process is to cause pressure bonding of pseudo-equiaxed crystals nucleated around the dendrite fragments and thus obtain a fine, segregation-free central structure. The concept of the process is shown schematically in **Fig. 1**. The required amount of reduction is expressed by Eq. (1).

$$\delta = \delta_1 + \delta_2 + \delta_3 \cdots\cdots\cdots\cdots (1)$$

where δ_1: amount of reduction required to expel the volumetric fraction of enriched molten steel in the solidus-liquidus coexistence region

δ_2: amount of reduction corresponding to the volume of the solid phase in the solidus-liquidus coexistence region which is crushed and expelled upstream

δ_3: reduction lost to metal flow in the completely solidified layer

The state of solidification of the bloom at the forging position is defined by a solidification profile obtained by heat transfer analysis,[10] assuming forging is not applied. The unsolidified thickness sandwiched by upper and lower solid fractions (solidus ratio: 1.0) at the forging position is termed the apparent unsolidified thickness d. The solid fraction at the center of the bloom is termed the apparent solid fraction f_S.

(1) Estimation of δ_1

In Fig. 1, the amount of enriched molten steel in the solidus-liquidus coexistence region, shown by the hatching inside the solidus line, can be calculated if it is possible to determine the apparent solid fraction f_S in the central area at the reduction position and the thickness of the solidus-liquidus coexistence region characteristic of the steel grade. **Figure 2** shows the results of a calculation of δ_1 for a wire rod material with a C content of 0.80%. When the apparent solid fraction f_S is 0.5 to 1.0, the amount of reduction δ_1 required to expel the enriched molten steel is calculated at 300 mm. The value δ_1 increases in proportion to the thickness of the bloom, a tendency which remains the same even as the C content increases. Internal cracking occurs if the amount of reduction δ_1 is inadequate, because the upper and lower reduction do not counterbalance each other at the bloom center, but rather are absorbed by the bending energy of the solidifying shell.

(2) Estimation of δ_2

The value δ_2 is the amount of reduction required to positively crush dendrite and cause the formation of a solidus-liquidus coexistence region of pseudo-equiaxed crystals in the residual pool of molten steel. Calculation results for δ_2 are shown in Fig. 2,

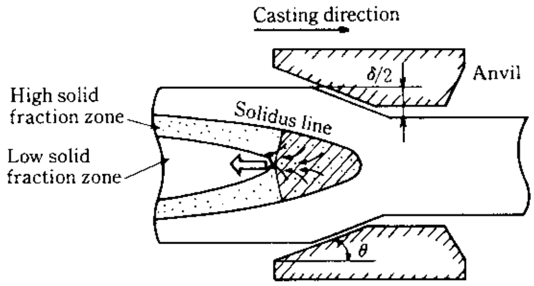

Fig. 1 Concept of continuous forging process

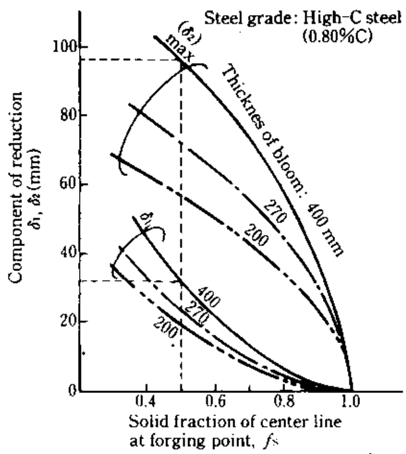

Fig. 2 Required amount of reduction to improve centerline segregation in continuous forging

together with the results for δ_1. This δ_2 shows the maximum value considered necessary to force out all the solid phase in the apparent unsolidified thickness d. From this figure, if f_S is in the range of 0.5 or over, δ_2 will have a maximum value of 50–100 mm.

(3) Required Amount of Reduction, δ
When the amount of reduction δ is not sufficiently larger than δ_1, only the movement of enriched molten steel will take place, causing minus segregation in the center of the bloom. Consequently, the required amount of reduction is the sum of the amount of reduction, δ_1, required to expel the the enriched molten steel and the amount of reduction, δ_2, required to expel the solid phase in the solidus-liquidus coexistence region, plus an amount of reduction lost to metal flow in the completely solidified layer, δ_3. For example, with a high carbon steel bloom 400 mm in thickness, if the apparent solid fraction at the forging position is 0.5 and δ is put at approximately twice δ_1, the required amount of reduction is 60 mm.

Summarizing the thinking described above, **Fig. 3** shows a conceptually predicted arrangement of the phenomena which may occur during the forging of an unsolidified bloom. The horizontal axis represents the forging position, with upstream points to the left. Point E is the point of complete solidification when forging is not applied. The vertical axis shows the amount of reduction.

When the amount of reduction is small and the amount of unsolidified material is large, internal cracking occurs because the solidus line does not undergo pressure bonding. If the amount of reduction and the amount of unsolidified material are both small, the only result is a concentration of enriched molten steel in the central area, accelerating centerline segregation. In the region of increasing reduction, negative segregation occurs when the amount of center-area reduction is smaller than δ_1. Improvement in centerline segregation begins when the amount of reduction exceeds the value of δ_1.

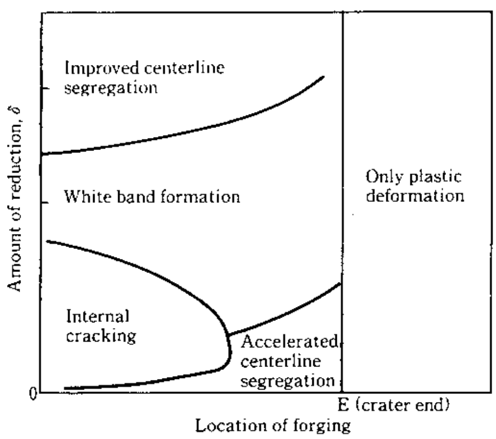

Fig. 3 Relation between internal quality of forged bloom and reduction behavior

2.3 Method of Reduction

Methods of realizing sufficiently large reduction relative to δ_1, for example 60–80 mm, include reduction by rolls and continuous forging. However, the roll reduction method[11,12] is considered less effective than continuous forging in crushing crystal grains because the solidus line normally remains in the same state with the passage of time. In addition, a large radius of curvature is needed in the area of reduction in order to prevent cracks at the solidus line, but as shown in **Fig. 4**, the diameter of the rolls would need to be extremely large to secure the same radius of curvature in the roll reduction method as that used in the continuous forging method. This condition, together with need for high torque in the roll drives, would require equipment of excessive size.

On the other hand, with the continuous forging process, the solidus-liquidus coexistence region directly under the forging mechanism is crushed in one forging pass, and the enriched molten steel and crushed crystal grains are effectively expelled upstream. At the same time, because this process offers good reduction efficiency at the bloom center, it is capable of preventing

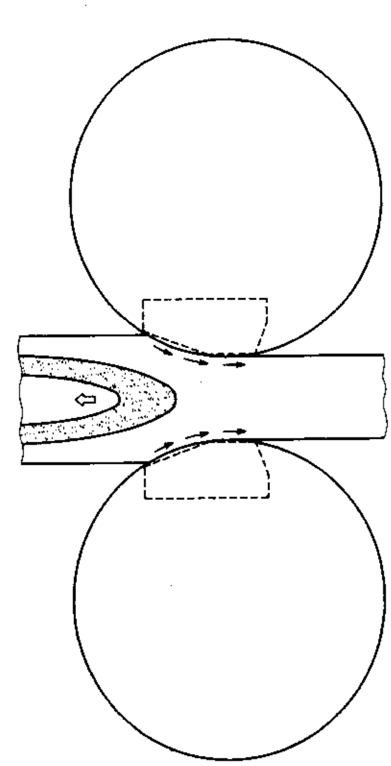

Fig. 4 Comparison of roll reduction and continuous forging process

internal cracking, even under high reduction, by forming a compressive stress field. In addition, there are few limitations on the amount of reduction because the problem of transmitting rotating torque, required in the roll reduction method, does not occur with continuous forging.

For the type of heavy reduction described above, the roll reduction method is unrealistic in terms of equipment and is difficult to apply. In contrast, the continuous forging method is superior to the roll reduction method in both quality and equipment aspects. This method was therefore adopted as the reduction method.

2.4 Distribution of Stress and Strain in Blooms during Forging

Because unsolidified blooms are subject to reduction in the continuous forging method, the process can cause internal cracking during forging if reduction is not conducted under proper conditions. Depending on conditions, surface cracks are also possible. For this reason, stress and strain in the bloom during forging were analyzed by the rigid-plastic finite element method (FEM) to understand these factors. An example of the results is shown in **Fig. 5**. This example is a case in which the solid phases were pressure bonded, and forging force satisfactorily reached the interior of the bloom. The main forging conditions were a bloom thickness of 270 mm, an unsolidified thickness of 20 mm, and reduction of 40 mm. The method of analysis was ridig-plastic FEM with 50 elements. The boundary conditions for the right and left edges were "movement maintaining a plane surface."

From this figure, it is considered that the entire area around the solidus line is subject to compressive stress during forging, and consequently, internal cracking does not occur. The tensile stress in the surface area is within the allowable value for the temperature conditions, and it is therefore assumed that surface cracking does not occur. Accordingly, it can be said that forging is possible without either internal or surface cracks, provided appropriate forging conditions are applied.

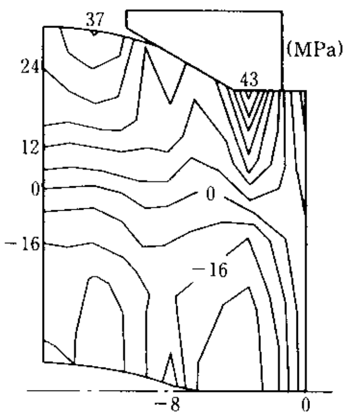

Fig. 5 Example of stress analysis of forged bloom

3 Experimental Method

3.1 Experimental Apparatus

Continuous forging equipment was installed at Mizushima Works No. 1 CC[13] and No. 3 CC.[14] Forging experiments were conducted with this commercial equipment to verify the concept of continuous forging and obtain quality confirmation. The main specifications of the continuous casters and continuous forging equipment are shown in **Table 1**. The position of forging equipment installation was 16 m from the meniscus at No. 1 CC and 26.4 m from the meniscus at No. 3 CC.

Table 1 Main specifications and casting conditions

	Mizushima No. 1 CC	Mizushima No. 3 CC
Continuous caster		
Machine type	Curved type (12.5 m)	Curved type (12.5, 22 m)
No. of strand	6	4
Bloom size (mm²)	270×340	400×560
Ladle capacity (t)	180	180
Continuous forging equipment		
Method of reduction	Oil hydraulic reduction lever	Electric motor driven crank
Amount of reduction (mm)	20∼100	40∼150
Location[a] (m)	16	26.4
Casting conditions		
Casting speed (m/min)	0.65∼0.75	0.4∼0.6
Specific water amount (l/kg)	0.75∼0.9	0.3∼0.5
Super heat (℃)	12∼36	15∼40

[a]Distance from meniscus

3.2 Experimental Conditions

An outline of the experimental conditions is presented in **Table 2**. Object steel grades included wire rod material, bearing material, structural steel, and materials for seamless pipe. The unsolidified thickness d during casting was controlled mainly by modifying the casting speed. Forging was conducted with the reduction ratio δ/d varied in the range of 0.3 to 8. The unsolidified thickness was estimated by a solidification calculation[10] using two-dimensional progressive differential calculus. The reliability of the solidification calculation was shown to be of adequate accuracy by measuring the thickness of the solidified shell by the riveting method, with confirmation by measurement of the surface temperature of blooms.

Table 2 Experimental conditions of continuous forging

	Mizushima No. 1 CC	Mizushima No. 3 CC
Steel grades	Ordinary steel Low alloy steel (0.05~1.0%C)	Ordinary steel Low alloy steel (0.10~1.0%C)
Unsolidified thickness d (mm)	0~120	0~70
Amount of reduction δ (mm)	20~100	40~140
Reduction ratio δ/d	0.3~7	0.8~8
Reduction length/chance (m)	10~180	20~100
Surface temperature of bloom (℃)	870~930	880~950

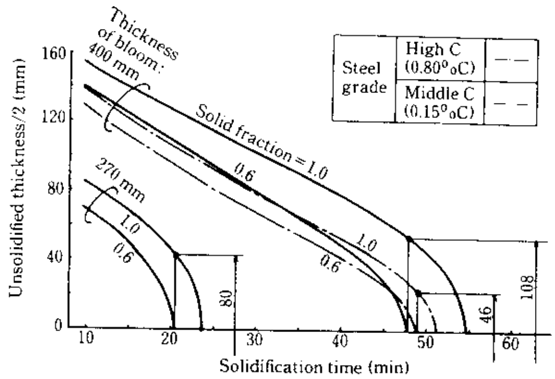

Fig. 6 Influence of steel grade and bloom size on unsolidified thickness

3.3 Content of Investigation

Central segregation behavior was investigated under varying forging conditions using several steel grades.[15,16] To determine the consistency of the quality of forged materials, we also investigated the behavior of materials when forging was continued over a long period, and behavior when casting was temporarily stopped and then restarted during casting.

The macro-segregation of blooms was investigated from the average value of ten 5-mm-ϕ drill samples. Semi-macro segregation was investigated with a macro-analyzer using beam diameters of 20 μm and 100 μm.[17]

4 Quality Improvement in Blooms after Continuous Forging

4.1 Effect of Various Factors on Centerline Segregation

The principal factors in centerline segregation in forging are the solidus-liquidus ratio in the bloom center at the forging position, the bloom size and composition, and the amount of reduction. In other words, centerline segregation is determined by what kind of forging (mainly the amount of reduction) is applied to what type of bloom (mainly the bloom size and material composition) at what point (mainly the solid fraction at the bloom center). Forging results differ depending on the relationship between the amount of forging and the solid fraction at the bloom center at the point at which forging is performed. However, if the unsolidified thickness is excessive due to a low solid fraction, the amount of reduction necessary to prevent internal cracking will be unrealistic. Experiments were therefore carried out in an object range of $f_S \geqq 0.5$.

4.1.1 Effect of size and composition on unsolidified thickness

The main factors affecting the bloom solidification profile are composition and bloom size. **Figure 6** shows an example comparing the relationship between these factors and the solidification profile at positions where the solid fraction is 0.6 and 1.0. The solidus-liquidus coexistence region becomes thicker as chemical elements increase, and the unsolidified thickness increases accordingly. Moreover, the unsolidified thickness increases as the thickness of the bloom increases because the speed of solidification decreases at the solidus line. The unsolidified thickness d between the solid fractions having values of 0.6 and 1.0 is 108 mm with a 400-mm-thick bloom of 0.8% C steel. With 0.15% C steel and the same 400-mm-thick bloom size, the value of d is 46 mm. Conversely, with the 0.8% C content and a 270-mm bloom thickness, d is 80 mm. In other words, appropriate forging conditions must be decided in consideration not only of the bloom thickness, but also of material composition.

4.1.2 Effect of apparent unsolidified thickness on centerline segregation

The effect of the apparent unsolidified thickness d on centerline segregation at a constant amount of reduction was studied at No. 1 CC and No. 3 CC. In this work, d was determined by varying the casting speed. The results are shown in **Fig. 7**. With d in the range of 20–40 mm, the carbon segregation ratio C/C_0 (C_0: ladle analysis) decreases and negative segregation increases. This phenomenon is attributed to the fact that crushed solid phase will be forced upstream if the apparent unsolidified thickness is too great relative to the amount of reduction. In other words, these changes result from an inadequate δ_2.

4.1.3 Effect of forging conditions on centerline segregation

The effect of forging conditions on C/C_0 at the bloom center can be arranged as δ/d, which is the ratio of the amount of reduction δ to the apparent unsolidified thickness d. The results are shown in **Fig. 8**, which indicates that C/C_0 gradually increases from

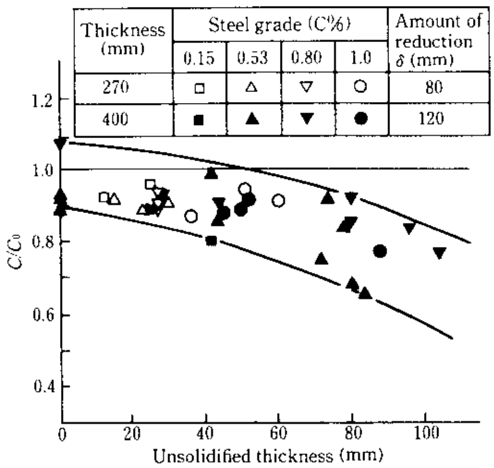

Fig. 7 Influence of unsolidified thickness on centerline segregation

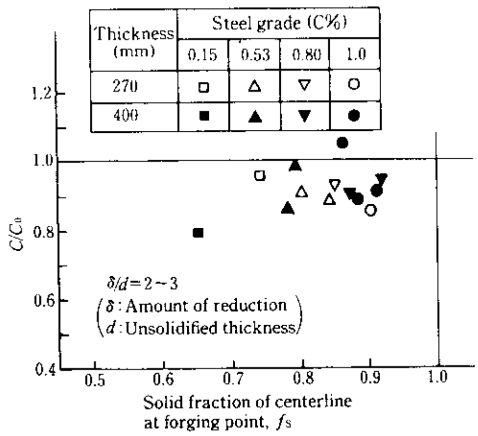

Fig. 9 Relation between fraction of solid at forging location and centerline segregation

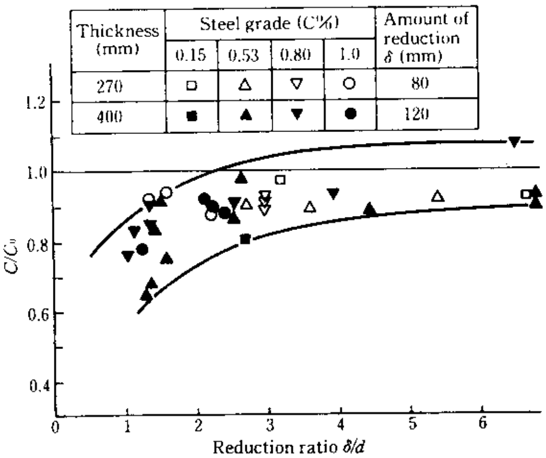

Fig. 8 Effect of reduction ratio (δ/d) on centerline segregation

negative segregation as δ/d increases, and the degree of segregation can be controlled to an aimed value between 0.6 and 1.0. To achieve $C/C_0 \geqq 0.9$, δ/d must be increased to 2 or over.

Specifically, as the amount of reduction necessary to achieve improvement in centerline segregation, it is estimated that reduction which only expels the liquid phase from the solidus-liquidus coexistence region is inadequate; an additional amount equivalent to that necessary to crush the solid phase and form pseudo-equiaxed crystals from the crushed matter is also required.

Figure 9 shows the relationship between the apparent solid fraction f_S at the bloom center and C/C_0 when $1.5 \leqq \delta/d \leqq 3.0$. No meaningful difference in C/C_0 can be seen with increases in f_S.

Accordingly, if it is possible to obtain an amount of reduction equivalent to the apparent solid fraction at the forging position, equal forging results can be obtyained. Considering the rolling process which is applied to the forged bloom, smaller amounts of reduction are desirable. As one example, Eqs. (2) and (3) show the desirable forging conditions when the object material is mild steel with a C/C_0 ratio near 1.

$$f_S \geqq 0.7 \quad \cdots\cdots (2)$$

$$\delta/d \geqq 2.0 \quad \cdots\cdots (3)$$

4.2 Effect on Crystal Grain Refinement

Photo 1 shows the macrostructure near the center of high carbon steel blooms (0.82% C) at cross-sections lying along the longitudinal axis. The V-shaped segregation line in a comparison material was alleviated by forging, and the crystal grain size in the central area showed marked refinement. Greater homogeneity can also be observed in the forged material. The results of a liquid penetrant test confirmed that porosity is completely eliminated and cracks do not occur in forged material.

Semi-macro segregation was examined using a macroanalyzer to determine the degree of P segregation and segregated grain size of P at the bloom center. The results of a measurement of segregation distribution confirmed that the number of micro-segregatiuon spots decreases in forged material. The relationship between the size and number of segregated spots is illustrated in **Fig. 10** (beam diameter: 100 μm), which shows that forging causes a large decrease in the number of P segregation spots when $C/C_0 > 4.0$, and is particularly effective in alleviating this problem when the concentration is high and the diameter of segregation spots is large, and produces segregation spots which are dispersed, of relatively low concentration, and small in diameter. This is considered to be because the enriched liquid phase between the dendrite arms is forced out

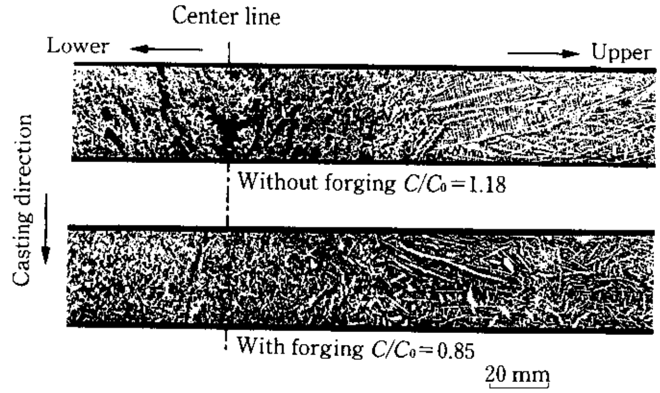

Photo 1 Macro-structures of forged blooms (longitudinal sections)

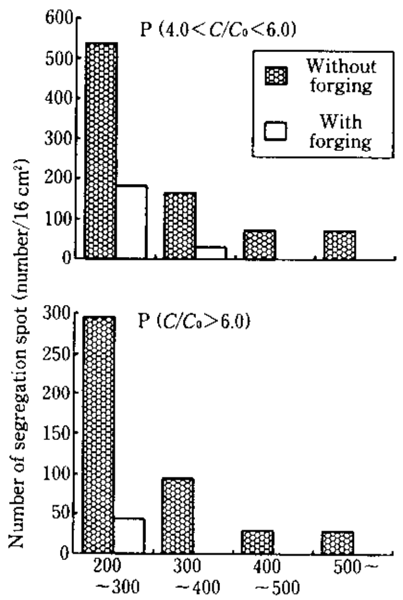

Fig. 10 Effect of forging on numbers of segregation spot in bloom (solid fraction $f_S = 0.78$)

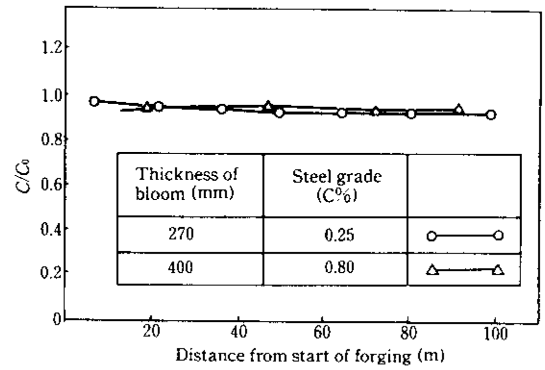

Fig. 11 Transition of centerline segregation along longitudinal axis during extended foring operation

by forging. It may therefore be understood that semi-macro segregation is also alleviated by continuous forging.

4.3 Stability of Quality during Long-Term Forging and in Non-steady States

In order to clarify the stability of quality in an extended continuous forging operation, forging was conducted for 2.5 h with 270-mm-thick blooms and for 3.0 h with 400-mm-thick blooms, and changes in the C/C_0 ratio at the bloom center were examined along the longitudinal axis. Samples were taken from cast blooms at intervals of approximately 10 m using a 5-mm ϕ drill. **Figure 11** shows the investigation results for carbon segregation.

The C/C_0 ratio reaches a steady state soon after the start of forging and the degree of segregation remains unchanged, demonstrating that quality is stable even in extended forging.

Next, to clarify the effect of changes in casting speed, casting was stopped for 1 min after 1 h of continuous forging, after which casting was resumed. An investigation was then made of the sulfur print in the longitudinal cross-section of a bloom corresponding to the interruption in casting and changes in the C/C_0 ratio along the longitudinal axis. The results were substantially identical to those obtained with blooms from steady-state casting, and showed no significant difference from such materials. This finding indicated that even fairly large changes in the casting speed during continuous forging cause no change in forging results, and clearly demonstrated that the process is superior in terms of quality under fluctuating operational conditions.

5 Conclusions

A continuous forging method was developed with the aim of improving centerline segregation in continuously cast blooms. In this method, anvils are used to apply heavy reduction to the unsolidified bloom during casting. The results of quality confirmation experiments with commercial equipment showed a marked improvement in quality, as summarized below. The process has been applied to an actual production process, confirming the possibility of its application as a practical technology.

(1) As the amount of reduction necessary to improve centerline segregation, the amount of reduction δ_1 needed to expel enriched molten steel from the solidus-liquidus coexistence region is inadequate; an amount of reduction δ_2 capable of crushing dendrite and expelling it into the unsolidified region as pseudo-equiaxed crystals is also needed. The necessary amount of reduction is decided from the material size and steel grade.

(2) The degree of central-area segregation C/C_0 resulting from reduction can be arranged in terms of the apparent solid fraction f_S at the bloom center at the point of reduction and the ratio of the amount of reduction δ and the apparent unsolidified thickness d. Internal cracking occurs in the region where the amount of reduction is small relative to the unsolidified thickness, but the quality approaches the improvement region through negative segregation as the amount of reduction increases.

(3) It is possible to control the degree of segregation to an aimed value between 0.6 and 1.0. Realistically, values of $f_S \geqq 0.7$ and $\delta/d \leqq 2.0$ are desirable in consideration of the downstream rolling process.

(4) Crystal grains at the bloom center are refined by forging.

(5) Semi-macro segregation is alleviated by forging; in particular, the incidence of high-density, large-diameter segregation spots is reduced.

(6) During extended forging operation, the degree of carbon segregation at the bloom center shows little change and remains stable over approximately 3 h of continuous forging. Moreover, the degree of segregation remained virtually unchanged with fluctuations in casting speed equivalent to an approximately 1 min stop of casting, confirming the stability of quality under standard operating procedures.

References

1) T. Ohno: "Kinzoku gyoukogaku," (1977), 97, [Chijin Shokan]
2) T. Watanabe, A. Sato, K. Yoshida, M. Toyota, and M. Kawasaki: *CAMP-ISIJ*, **2**(1989)4, 1146
3) H. Yamasaki, Y. Shinjyo, K. Kinoshita, and K. Nakanishi: *Tetsu-to-Hagané*, **71**(1985)4, S208
4) M. Suito, M. Kawaberi, J. Hasunuma, and Y. Shinjyo: *Tetsu-to-Hagané*, **71**(1985)4, S210
5) Y. Habu, S. Itoyama, T. Emi, and K. Sorimachi: *Tetsu-to-Hagané*, **67**(1981)9, 1498
6) T. Tomura, Y. Habu, G. Kawanishi, T. Emi, and K. Sorimachi: *Tetsu-to-Hagané*, **66**(1980)12, S798
7) M. Yamada, S. Ogibayashi, M. Tezuka and T. Mukai: Steelmaking Conference Proceedings, ISS, Toront (Canada), **71**(1988), 81
8) H. Kobayashi, S. Kuriyama, T. Masaoka, M. Suzuki, and S. Miyahara: *CAMP-ISIJ*, **2**(1989)4, 1158
9) S. Kojima, T. Imai, T. Fujimura, and H. Mizota: 4th International Conference on Continuous Casting, Brussels (Belgium), (1989), S306
10) T. Matsukawa, S. Yuhara, S. Kojima, T. Fujiyama, and S. Miyagawa: *Kawasaki Steel Giho*, **19**(1987)1, 7
11) E. Takehara, T. Yamasaki, J. Kadoi, K. Hayashi, and H. Akita: *Tetsu-to-Hagané*, **60**(1974)7, 875
12) I. Takagi, S. Kawasaki, Y. Kanezuka, K. Ebina, and K. Ayata: *CAMP-ISIJ*, **4**(1991)1, 297
13) S. Kojima, T. Matsukawa, T. Imai, H. Mizota, M. Kawaberi, and H. Yamasaki: *Tetsu-to-Hagané*, **73**(1987)4, S209
14) S. Kojima, H. Mizota, T. Matsukawa, F. Sudo, T. Fujimura, and Y. Yoshimoto: *CAMP-ISIJ*, **4**(1991)1, 293
15) K. Kushida, T. Fujimura, T. Imai, S. Kojima, I. Tanokuchi, and T. Kayano: *Tetsu-to-Hagané*, **73**(1987)4, S210
16) K. Kushida, T. Fujimura, H. Mizota, S. Kojima, H. Imamura, and H. Yamasaki: *CAMP-ISIJ*, **1**(1988)1, 207
17) K. Kushida, T. Fujimura, H. Bada, T. Matsukawa, K. Akimoto, and N. Hamanishi: *CAMP-ISIJ*, **4**(1991)1, 294