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Production Facilities and Operational Techniques for Continuous Forging Process

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To solve the problem of segregation in continuous casting, the continuous forging process was developed and installed at No.3 Continuous Caster of Mizushima Works as the first facility of its kind in the world. The process has been successfully applied in commercial operation to the production of high quality CC blooms with no centerline segregation or negative centerline segregation. Special care was taken in designing a process for a multi-strand caster to simplify the facility and reduce the investment cost by adopting a crankshaft system driven by a single motor. The degree of centerline segregation can also be controlled within the range of negative to positive, depending on customer requirements, by choosing an appropriate solid fraction during forging.

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1 Introduction

In the past, magnetic stirring[1,2] and soft reduction[3,4] were adopted in practical operation with the aim of improving centerline segregation in continuously cast blooms, and the low temperature casting method[5] was applied to increase the ratio of equiaxed crystals, but room remained for improvement in the prevention of semi-macro segregation and other problems.

Considered the limited potential for future development in these conventional methods, a method of heavy reduction in the unsolidified state[6-10] was developed as a new process for improving centerline segregation. In this new process, blooms are continuously subjected to heavy reduction during the final stage of solidification, forcing out the enriched molten steel while forcibly pressure-bonding the solid surface.

In 1985, test equipment was installed at Mizushima Works No. 1 Continuous Caster, and experiments were conducted to verify the principle described above. The results of an investigation of various steel grades demonstrated that, by selecting appropriate forging conditions, it is possible to eliminate centerline segregation without causing internal cracks, and when necessary, to control the segregation of the central area to a negative value.

Following the confirmation of these ground-breaking results, the process was applied to commercial production, and high-efficiency forging equipment suitable for a multi-strand operation was developed. In 1990, the world's first practical production equipment of this type[11] was put into operation at Mizushima Works No. 3 CC.

Mass production techniques were established with this practical unit, the expected superior product features were confirmed, and production for sale began in 1991. Stable production has been maintained until the present, contributing to quality improvement and the development of new products.[12]

This report presents an outline of the practical production facilities and describes the operational techniques used with this equipment.

2 Tasks for Practical Application

The necessary conditions for practical use of the continuous forging method and tasks for responding to these requirements are shown in **Fig. 1**. The principle of this technology is to control centerline segregation while preventing internal cracks by applying heavy reduction to blooms during solidification. For practical use, it is necessary to establish technology which makes possible stable, long-term operation together with technology which does not leave anvil shape on the surface

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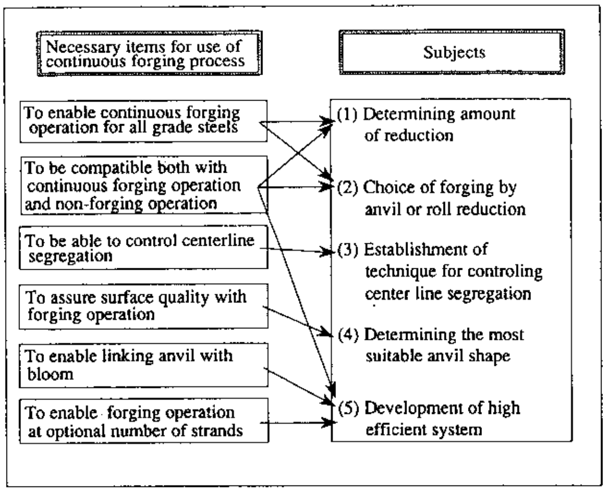

Fig. 1 Main subjects to be solved for practical use of continuous forging process

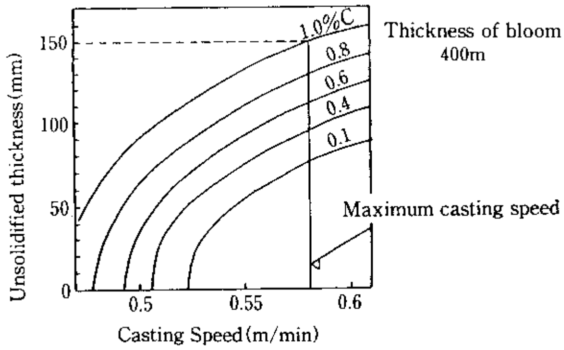

Fig. 2 Relationship between casting speed and unsolidified thickness

attributable to forging after rolling. These technologies are interrelated, but fundamentally, it is essential to control the amount and method of forging and the state of solidification of the bloom at the forging position; the desired goals must be achieved using this combination.

In applying this continuous forging method to an actual continuous casting machine, the first problem is equipment-related spatial restrictions. In particular, installation at an existing multistrand continuous caster requires an equipment design capable of simultaneously forging the multiple strands. In addition, because blooms are drawn out of the caster during forging, it is important to achieve perfect synchronization between the movement of the bloom in the casting direction and the movement of the anvils. Finally, it is important to establish techniques which effectively use the continuous forging process not only from the the start of operation through steady-state casting, but also at the end of the casting operation.

3 Fundamental Concept of Continuous Forging Equipment

3.1 Determining Necessary Amount of Forging

In eliminating centerline segregation, it is necessary to apply an appropriate amount of forging reduction, corresponding to the thickness of the solidus-liquidus coexistence region of the bloom prior to the completion of solidification. The thickness of this coexistence region is determined mainly by the time (called "travel time") required for the material to travel from the mold to the forging device. After the installation position of the forge is decided, the casting rate is decided for each steel grade; this in turn determines the productivity of the continuous caster. It is therefore necessary to decide the position of forging-equipment installation so as to obtain an appropriate solidus-liquidus coexistence region thickness for all materials subject to forging, while also considering caster productivity. The forging equipment at Mizushima Works No. 3 CCM, which was to be located within the existing continuous casting line, was installed after the pinch roll from the viewpoint of equipment space limitations and maintaining the previous level of productivity.

The main factors which affect the thickness of the solidus-liquidus coexistence region are the bloom size and steel composition. Where the effect of bloom size is concerned, the thickness of this coexistence region increases as the thickness of the bloom increases. Among compositional effects, the influence of the carbon content is striking. As shown in **Fig. 2**, the unsolidifid thickness increases in proportion to the carbon content.

In determining the necessary amount of forging reduction, after the thickness range of the solidus-liquidus coexistence region is decided, the equipment specification for the maximum forging amount is determined from the maximum unsolidified thickness. This is because an amount of forging capable of completely pressure-bonding the upper and lower solid fractions is needed in order to eliminate centerline segregation. In actual operation, the appropriate amount of forging is selected in consideration of the following conditions:

(1) Product Quality Conditions
Degree of segregation in central-area enrichment decided from the required properties of the product.
(2) Restriction Related to the Rolling Process
Shape conditions related to the reduction ratio in rolling, final product thickness, rolling yield, etc.
(3) Casting and Forging Process Conditions
Conditions required to avoid surface and internal cracks, and limitations on forging reduction force.

The continuous forging process at Mizushima No. 3 CCM is an example of actual implementation. The thickness of the solidus-liquidus coexistence region (unsolidified thickness) at the forging position is shown in Fig. 2. From the viewpoint of preventing internal cracks, the maximum casting speed is 0.58 m/min. Under these conditions, the maximum amount of reduction we set at 150 mm based on the unsolidified thickness of a 1.0% C steel.

3.2 Study of Reduction Methods

With heavy reduction of 150 mm, an equipment configuration using the roll reduction method would be extremely unrealistic. Because the continuous forging method is superior to roll reduction in terms of both quality and equipment, continuous forging was selected as the method of reduction.

In using anvils to forge blooms during continuous casting, there is concern that the resistance of the anvils may cause fluctuations in the casting speed, with a harmful effect on both operations and quality. Because the casting speed is controlled by the pinch rolls of the continuous casting machine, the structure and control of the forging device must ensure that the movement of the anvils during forging is synchronized with the bloom with good accuracy.

The reduction mechanism used in the continuous forging process is shown in **Fig. 3**. The reduction mechanism has a crank structure, making it possible to separate reduction force and reduction torque, and the anvils rotate freely on the crankshaft, allowing free movement in the casting direction. During forging, the anvils cause virtually no change in the drawing force acting on the bloom and can move in synchronization with the bloom. For this reason, a control device for synchronization with the pinch rolls is unnecessary.

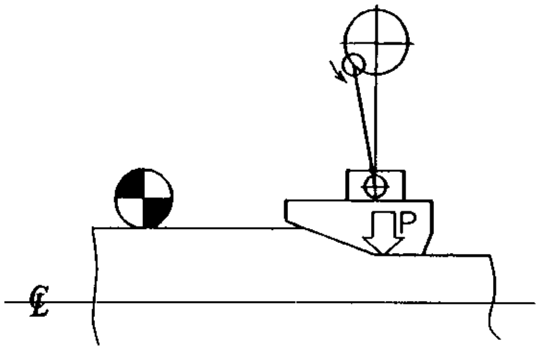

Fig. 3 Method of forging by anvil

3.3 Optimization of Forging Anvil Configuration

It is necessary to decide the anvil shape for continuous forging in a way which will not produce cracking in blooms during forging. The cross-sectional configuration of an anvil in the casting direction, as shown in **Fig. 4**, comprises three elements, the angle of inclination θ (degree), the length of the tapered section, l_1 (m), and the length of the flat section, l_2 (m), whose respective values are decided by the following method.

The optimum value of the angle of inclination θ is

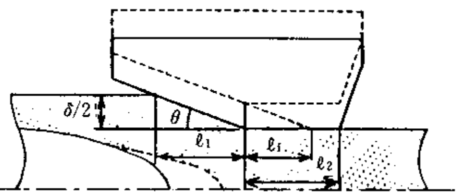

Fig. 4 Cross section of anvil and bloom along casting direction at the start point of forging

decided from the following three viewpoints:

(1) Prevention of Sliding between the Anvils and Bloom
It is necessary to satisfy $\theta \leqq$ friction angle ($\tan^{-1}\mu$). The symbol μ represents the coefficient of friction between the anvil and bloom, and in hot forging, is generally on the order of 0.35. Thus, the friction angle is $\theta \leqq \tan^{-1} 0.35 = 20°$.

(2) Prevention of Internal Cracks
Stresses generated in the bloom during forging must be under the allowable values for the temperature of the bloom. Generated stresses were analyzed by the two-dimensional rigid-plastic finite element method, confirming that the solidus interface is under compressive stress.

(3) Expulsion of Enriched Molten Steel
Larger values of θ are desirable.

Based on the foregoing, the anvil angle was set at the largestr value within the range permitted by (1) and (2).

Next, the taper legnth l_1 was decided geometrically from the amount of forging reduction, δ (m), and the angle of inclination, θ, as shown by the following equation:

$$l_1 > \delta/(2 \tan\theta) \quad \cdots\cdots (1)$$

The flat length l_2 was set at a value larger than the amount of forward transfer l_f of the anvil in the casting direction during one forging stroke, based on the condition that "step" marks should not be present on the forged surface of the bloom after forging.

$$l_2 > l_f, \quad l_f = V_c \cdot t \quad \cdots\cdots (2)$$

where, V_c is the casting velocity, and t is the forging reduction cycle (min).

4 Development of High-Efficiency Mass-Production Equipment

4.1 Outline of Continuous Forging Equipment at No. 3 CCM

No. 3 CCM is a curved-type machine used for both blooms and beam blanks, and has the main specifications shown in **Table 1**. The location of forging equipment installation is between the pinch rolls and the dummy bar table, as shown in **Fig. 5**. The existing caster dummy bar table was moved downstream to allow

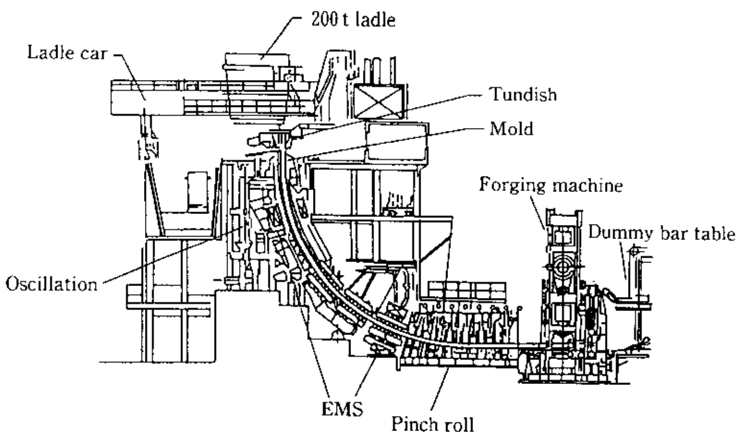

Fig. 5 Schmatic diagram of No. 3 CCM at Mizushima Works

Table 1 Main specifications of Mizushima No. 3 CC

Machine type		Curved type
Size	Bloom (mm)	400×560 300×400
	Beam blank (mm)	400×460×120
No. of strands		4
Curved radius(m)		12.5 22.0
EMS		strand+final (two points)

Table 2 Main specifications of continuous forging facilities

Method of reduction	Electric motor driven crank
Pressure of reduction	max. 1200 t
Amount of reduction	max. 150 mm
Forging location (distance from meniscus)	26 m
Motor	AC 900 kW

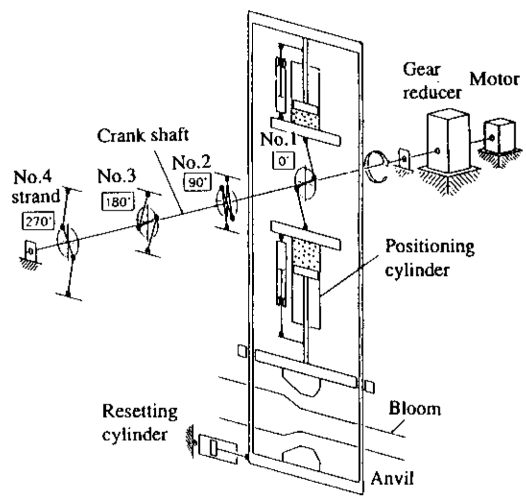

Fig. 6 Schematic diagram of continuous forging unit

this layout. This position, which is 26 m from the mold meniscus, was selected to secure an appropriate solidus-liquidus coexistence region thickness and maintain the same level of productivity as in the past. The main specifications of the forging equipment were decided as shown in **Table 2** using the concepts mentioned previously, with the bloom size and cast steel grades as standards.

4.2 Reduction Equipment

Electric motor and oil hydraulic methods are conceivable as the forge drive, but the motor method was adopted because it is superior to the hydraulic method in operating power costs, low noise, and maintainability.

A motor crank mechanism, shown in **Fig. 6**, was newly developed for the forging equipment. Because forging is achieved by the cranking action of the motor-driven crankshaft, forging can be conducted at four strands with a single motor by changing the forging time-phase at the respective strands. The amount of forging is set by changing the stroke of the positioning cylinder rods connected to the upper and lower anvils, making it possible to set forging conditions freely for each of the strands.

The forging unit moves in synchronization with the bloom by moving in a pendular manner during forging, with the crank shaft as the center of rotation. After the anvils are released from the bloom, the anvils is again moved in pendular fashion by the resetting cylinder,

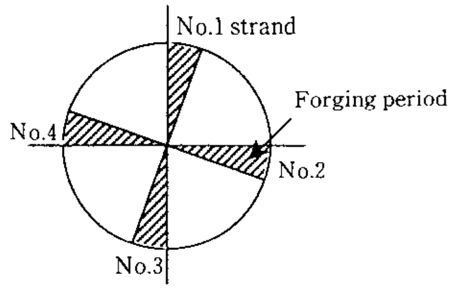

Fig. 7 Distribution of forging period in forging at four strands

which pulls the forging equipment back to its original position. This completes one forging cycle. By synchronous repetition of this motion, it is possible to achieve smooth continuous forging matched to bloom movement in the casting process.

This equipment was the first installed in a continuous casting line, and has the following features:

(1) The Equipment Is a Simple, Energy-Saving Device for Forging Multiple Strands
As shown in **Fig.** 7, the forging-period phases during one rotation of the crankshaft are staggered. It is therefore possible to forge multiple stands with one motor because the strands are forged in sequence rather than simultaneously. Thus, the equipment is simple and energy requirements are reduced.

(2) A Simple Following Mechanism Is Used to Synchronize the Forging Anvils and Bloom Movement in the Casting Process
Bloom/anvil synchronization is possible with the pendulum mechanism and resetting cylinder. Because the structure is simple, the equipment is less susceptible to problems and its reliability is high. The pendulum is long, reducing following resistance, and vertical movement due to the ratio of curvature is so small as to be negligible, enabling smooth synchronization.

(3) The Amount of Forging Reduction Can Be Set Independently for Each Stand, Giving the Forge High Flexibility
The rod stroke of the positioning cylinders can be set individually to control the amount of forging reduction; it is also possible to limit forging to only designated strands.

(4) Equipment Safety Is Guaranteed Even with Abnormal Loads
A relief valve for load pressure in the positioning cylinder provides a relief mechanism for overloads. This device for coping with any unlikely problems is safe and reliable.

All equipment is the company's original design. No particular problems have occurred in the three years since the start of operation, and the forging is functioning satisfactorily as equipment for practical use.

5 Establishment of Mass Production Operating Techniques

5.1 Establishment of Travel Time Control Technique

As a method of controlling centerline segregation in blooms,[13] control of the thickness of the solidus-liquidus coexistence region while maintaining a constant amount of forging reduction is suitable for practical operation, and was therefore adopted. The thickness of the coexistence region is mainly determined by the time to solidification, or more specifically, by the travel time required for the material to travel from the mold meniscus to the forging equipment. Accordingly, the degree of segregation at the bloom center can be controlled by controlling the travel time.

Figure 8 shows the relationship between the degree of centerline segregation and travel time with various steel grades when the amount of forging reduction is constant at 110 mm. Because the appropriate travel time differs depending on chemical composition, the travel time at which the carbon segregation ratio $C/C_0 = 1$ was taken as 100%, where C represents the concentration of carbon at the center of the bloom and C_0, the carbon concentration of the molten steel in the ladle.

This work demonstrated that the degree of segregation be controlled using travel time. Accordingly, if casting can be conducted at a uniform casting speed, a uniform travel time can be maintained, and it will be possible to maintain a constant degree of segregation. However, it is generally difficult to cast at a uniform speed in actual operation, and there are cases in which the casting speed varies temporarily due to various outside disturbances or operaional necessity. Without a corrective function which responds to these changes in casting speed, a constant degree of segregation cannot be maintained, causing quality nonconformance and decreases in yield. We therefore developed a casting speed control method capable of maintaining a uniform

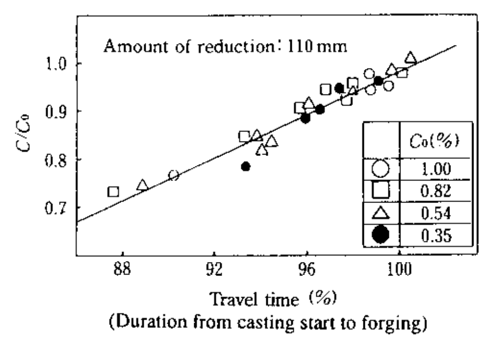

Fig. 8 Influence of travel time (duration from casting start to forging) on the extent of center line segregation

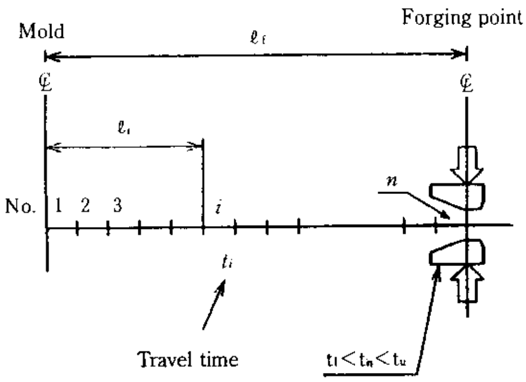

Fig. 9 Tracking method of controlling travel time

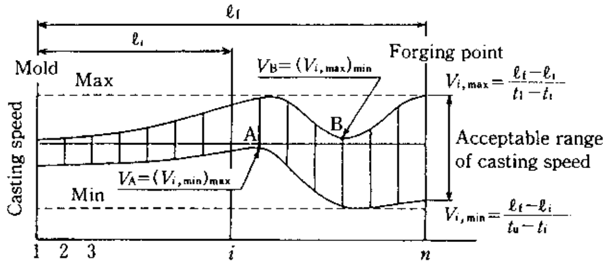

Fig. 10 Method of determining casting speed in control of travel time

travel time at the forging position even when some degree of fluctuation exists in the casting speed.

(1) As shown in **Fig. 9**, the bloom is divided into a plural number of blocks between the mold and the forging equipment (as an actual example, one block is 0.5 m in length), and the travel time t_l of each block is tracked from the mold.

(2) To achieve a uniform casting speed after a change in casting speed, the allowable casting speed range $(V_i)_{min}$ and $(V_i)_{max}$ for each block needed to maintain the allowable travel time at the forge is obtained, as shown in **Fig. 10**.

$$(V_i)_{max} = (l_f - l_i)/(t_l - t_i) \cdots\cdots\cdots\cdots (3)$$

$$(V_i)_{min} = (l_f - l_i)/(t_u - t_i) \cdots\cdots\cdots\cdots (4)$$

$$(V_i)_{min} \leqq V_i \leqq (V_i)_{max} \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

where V_i (m/min) is the allowable casting speed for block i, and l_f and l_i are respectively the distance from the forgeing equipment to the mold and the distance from block i to the mold. The symbols t_u and t_l represent the maximum and minimum travel time for the aimed degree of segregation; t_i is the travel time from the mold to block i.

(3) A casting speed (V) which falls within the allowable range over all the blocks is selected from Fig. 10 and used as the casting speed at that point in time. If casting speed variations are large, it may in some cases be impossible to set a speed which will satisfy the allowable range in all regions. In this case, the casting speed is selected based on the condition of minimizing the length of the nonconforming section.

$$(V_{i,min})_{max} \leqq V \leqq (V_{i,max})_{min} \cdots\cdots\cdots\cdots (6)$$

where V is the set casting speed at the point in time of tracking.

(4) The operation described above is tracked continuously and the optimum casting speed is set on a moment to moment basis, controlling the travel time to the aimed value.

(5) In the allowable speed setting described in (3), adjustments can frequently be made in the later blocks even if early blocks do not fall within the allowable speed range. This makes it possible to limit the control range to the later blocks from the beginning and still maintain control. This technique increases the allowable range of casting speeds and improves control response, and is therefore often effective in practical operation.

Using the casting speed control method described above, technology has been established for consistently and stably controlling the degree of segregation at the bloom center to a constant aimed value.

5.2 Forging Start Technique for Reducing Forge Capacity Requirements

The forging force at the start of forging is greater than that in steady-state operation because, as shown in **Fig. 11**, force equivalent to the surface area corresponding to the amount of bloom advance in one forging stroke is adequate for steady-state forging, while forging force equivalent to the entire surface area of the anvil is required at the start of forging. To reduce the reduction area at the start of forging, the amount of forging was considered to be distributed over several strokes, as shown in **Fig. 12**. The distributed-reduction start method reduces the reduction area per stroke, making possible a 10-25% reduction in forging force, which in turn reduces the capacity requirements of the forge.

In addition, when the forge is applied to a multi-strand operation, a higher motor capacity will be

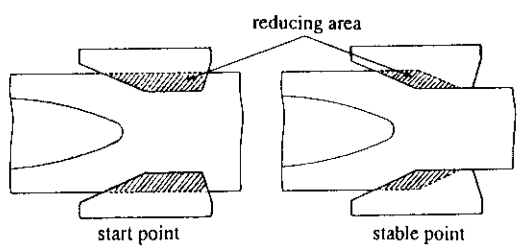

Fig. 11 Comparison of reducing area at start point with that at steady state period during the forging

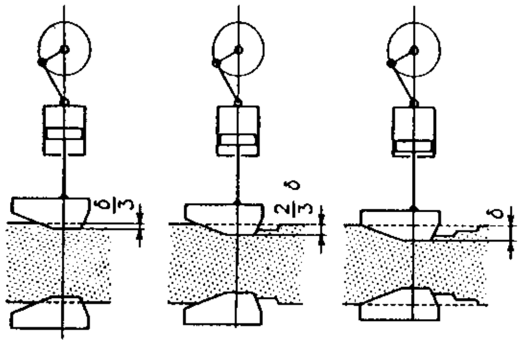

Fig. 12 Step-wise reduction method at the start point of forging

required if the start of forging at all strands is concentrated on the same cycle of crank operation than if forging is started on only one strand per cycle. For this reason, the start of casting is staggered from strand to strand, which means that the start of forging is also be staggered by at least one crank cycle.

5.3 Techniques for Operational Stability at Casting End

With material near the completion of a casting sequence, the tail-end of the bloom is seal-forging as a result of forging in a solidified state at the top end. In some cases, internal cracking occurs at the both sides of the bloom solidus-liquidus coexistence region during forging because the internal pressure is excessive. As a measure for preventing cracking, it is important not to cause abnormal internal pressure, and efforts were therefore made to delay the solidification of the tail-end of the bloom as much as possible.

The molten steel in the unsolidified portion remaining near the end of the bloom contracts volumetrically as solidification proceeds, while on the other hand, the remaining molten steel is forced upstream by forging. If the amount of remaining molten steel expelled by forging is greater than the amount of contraction attributable to solidification, there is a possibility of molten steel overflowing the end of the bloom, with a serious impact on the operation. Whether this happens depends on the forging conditions and steel grade. In the actual results of forging at Mizushima No. 3 CCM, the amount of overflow increases with the carbon content in high carbon steels. With steel grades having carbon contents of 0.7% or more, measures have been established to prevent overflow at the completion of casting, and stable operation has been realized.

4 Conclusions

With the aim of improving centerline segregation in continuously cast blooms, a continuous forging process using anvils was developed. The results of this unprecedented new method were then confirmed with test equipment. In progressing to the stage of actual production, high-efficiency equipment applicable to a multistrand operation and the related operational techniques were developed. The results obtained are summarized below.

(1) The necessary amount of forging reduction depends on the thickness of the solidus-liquidus coexistence region at the position where forging is performed. The thickness of this region is determined by the thickness of the bloom, casting speed, and the chemical composition (especially carbon) of the steel. In terms of hardware, the maximum amount of forging corresponds to the maximum thickness of the solidus-liquidus coexistence region under the casting conditions with the caster used.
(2) In the reduction mechanism, the use of a crank structure makes it possible to separate reduction force and reduction torque, which allows smooth movement of the anvils in synchronization with the bloom during reduction.
(3) To realize application to a multistrand continuous caster using simple equipment, a forging unit was developed which performs sequential forging of each strand by staggering the forging-period phase during one rotation of the crankshaft.
(4) To cope with changes in casting speed during casting, a casting speed control method was developed to maintain a constant travel time to the forging position, making it possible to maintain a uniform degree of centerline segregation.

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