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Production of High Quality Rod and Bar by Applying a Continuous Forging Process

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Production of High Quality Rod and Bar by Applying a Continuous Forging Process*

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1 Introduction

Almost all rod and bar products are subjected to such secondary working as forging, wire drawing, and thermal refining before they become final products. If material defects exist, such problems as cracking and wire breaking can occur in these secondary working processes. In other words, it can be said that secondary working itself provides a stringent total inspection of the goods in process. In recent years, secondary working has become more complex, resulting in the need for fewer defects and stricter quality control by the steelmakers.

One of the principal quality requirements is the elimination of center-line segregation in rod and bar products manufactured from continuously cast blooms. Although there are various techniques for reducing the centerline segregation in continuously cast blooms, none of them completely eliminates the problem, and can lead to other quality problems. Consequently, the conventional techniques for reducing centerline segregation fell short of satisfactorily meeting the strict overall quality requirements for high-grade rods and bars.

After considering unsurmountable limits of the conventional methods, Kawasaki Steel invented a new technique whereby molten steel concentrate in the center region of the bloom is continuously discharged toward the unsolidified side. This method uses a continuously applied heavy reduction to the bloom before its solidification ends and forms compulsorily the crater end of it (a continuous forging process), and has proved its remarkable improving effect.[1-3]

To apply this technique to the manufacturing proces, continuous forging equipment was installed with the No. 3 continuous bloom caster at the Mizushima Works in June 1990.[4,5] Rod and bar products to which this continuous forging process is applied have already been put into practical use, and a good reputation for improved quality has been obtained from customers.

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The authors are currently developing higher added-value rod and bar products by applying the continuous forging process.

This report describes the quality of rod and bar products produced by applying the continuous forging process.

2 Techniques for Reducing Centerline Segregation

2.1 Conventional Techniques for Reducing Centerline Segregation

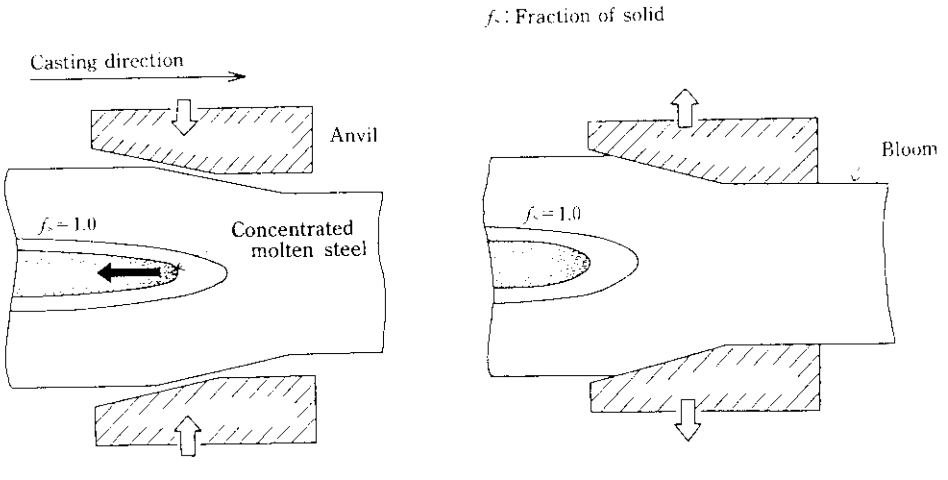
The conventional techniques for reducing the centerline segregation in continuously cast blooms include the electro-magnetic stirring of the molten steel before the end of the solidification period,[6,7] low-temperature casting by lowering the superheat of the molten steel in the tundish,[8] and the application of a light reduction to the bloom by rolls at the end of the solidification period.

Although each of these techniques is effective in reducing centerline segregation, they are not good enough to completely eliminate it. When the electro-magnetic stirring is employed, negative segregation occurs in the stirred portion. Therefore, it has proved impossible to conduct electro-magnetic stirring when a deviation in the depth of hardening poses a problem in the final product. When low-temperature casting is employed, it is difficult to separate the inclusions from the molten steel in the tundish by flotation, and the cleanliness of the molten steel decreases. Therefore, low-temperature casting is not the best method for steel grades that must provide high cleanliness, as with products requiring high rolling-contact fatigue life. The application of a light reduction to the bloom by rolls at the end of the solidification period has the problem of causing internal cracks in the bloom. Consequently, the conventional techniques for reducing centerline segregation cannot completely eliminate the problem, in addition to leading to other quality deterioration so that these methods did not meet the overall quality requirements for high grade rods and bars. Accordingly, for strict specifications that demand good quality free from centerline segregation, there was no way but using diffusion soaking to blooms.

2.2 Continuous Forging Process for Reducing Centerline Segnegation

As shown in **Fig. 1**, the continuous forging process applies a heavy reduction to the continuously cast bloom by anvils at the end of the solidification period so as to discharge the molten steel concentrate in the core of the bloom toward the unsolidified side (in the direction opposite to the casting direction), thereby forcibly forming solidification end point. Since the conventional centerline segregation method or any of its improvements can not discharge this molten steel concentrate, and the best it can do is to divide individual segregation areas into smaller areas, but the continuous forging process can make bloom free from segregation. Tapered anvils are used to apply the reduction until the bloom is reduced by a predetermined amount, after which the anvils leave the bloom. The bloom is continuously reduced by moving the anvils in the casting direction in a reciprocating motion according to fixed cycles.

While developing this technique, experimental equipment was installed[1] with the No. 1 continuous bloom caster at Mizushima Works, and experiments were conducted. As a result, centerline segregation was completely eliminated without causing any internal cracks in the bloom by selecting appropriate reduction conditions.[2,3] Continuous forging equipment was then installed with the No. 3 continuous bloom caster at Mizu-



Before forging

After forging

Fig. 1 Concept of continuous forging process

Table 1 Main specification of No. 3 bloom continuous casting machine and forging machine

Item	Specification
Continuous casting machine	
Machine type	Concast S
Casting radius	12.5 m, 22.25 m (tow points unbending)
Size of casting steel	300 × 400 mm² (bloom) 400 × 560 mm² (bloom) 120 × 400 × 460 mm (beam blank)
Number of strands	4
EMS	Strand + Final
Forging machine	
Machine type	Electric motor drived crank mechanism
Distance from meniscus	26.4 m
Amount of reduction	Max 150 mm (at 400 × 560 mm² bloom)

shima Works in June 1990, and this process is currently applied to the commercial production of rods and bars for specific uses.

The main specifications of the No. 3 continuous bloom caster and continuous forging machine at Mizushima Works are shown in **Table 1**. Based on optimum reduction conditions, the continuous forging machine is installed at a point 26.4 m from the meniscus, and the maximum amount of reduction is 150 mm for a bloom 400 × 500 mm². An electric motor driving a crank is used to apply the reduction. The mechanism is such as to gradually apply the reduction by changing the phase of four strands through the rotation of the motor-driven crankshaft.

Examples of the macrostructure in the longitudinal section of a bloom of high carbon steel with 0.82% C that was continuously forged are shown in **Photo 1**. To evaluate the centerline segregation of the blooms, samples were taken from the core of a bloom at 30-mm intervals in the casting direction by a 5-mm drill in diameter as shown in **Fig. 2**, a chemical analysis was conducted, and an evaluation was made according to the centerline segregation ratio (C/C_0) given by the following equation:

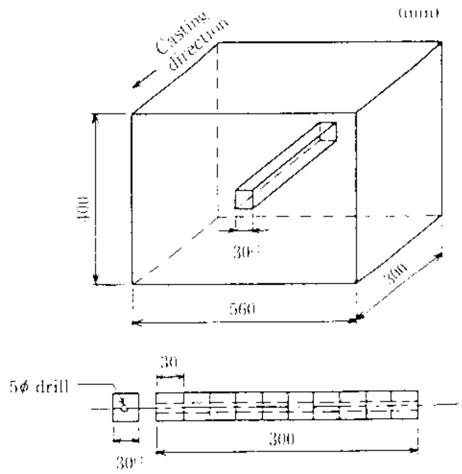


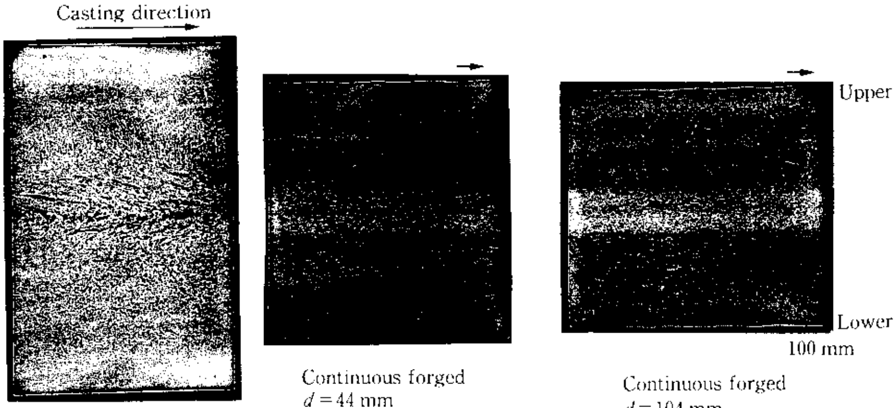
Fig. 2 Sampling method for analyzing centerline segregation

$$C/C_0 = \left(\sum_{i=1}^{10} C_i/C_0\right)/10 \quad \cdots\cdots\cdots\cdots (1)$$

where C_1: Value of check analysis of the core

C_0: Value of ladle analysis

As shown in Photo 1, the bloom cast by the conventional non-forged process had porosity and macro-segregation in the central region, as well as V-type segregation near the central region, while the continuously forged bloom had none of these defects. Furthermore, it is apparent that when the thickness of the unsolidified zone at the application of reduction, d, was increased by



Conventional
C/C_0[C] = 1.18

Continuous forged
d = 44 mm
C/C_0[C] = 0.91

Continuous forged
d = 104 mm
C/C_0[C] = 0.76

Photo 1 Macrostructures and centerline segregation ratio (C/C_0) of forged bloom

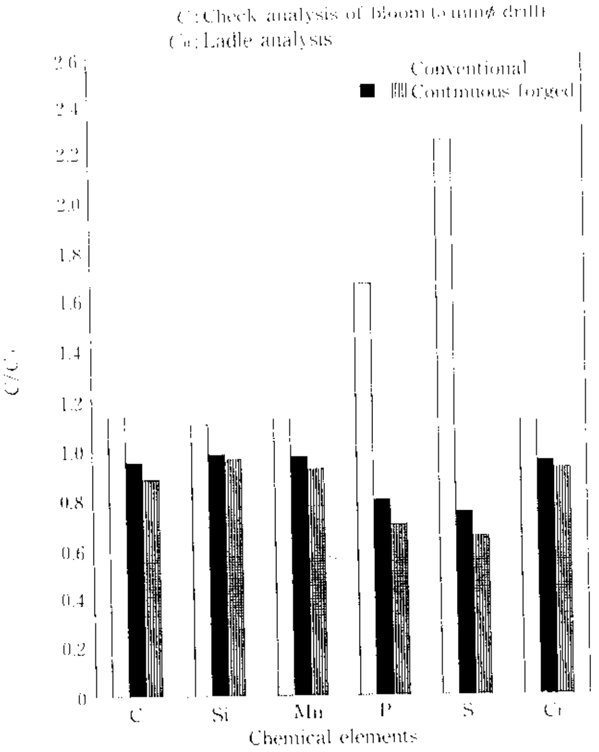


Fig. 3 Ratio of centerline segregation (C/C_0) of SUJ2 bloom

raising the casting speed, the zone of negative segregation in the central region became more marked and that the centerline segregation ratio C/C_0 of carbon shows increased negative segregation. It seems that the more the thickness of the unsolidified zone in the bloom is reduced, the greater the amount of molten steel concentrate discharged during reduction.[9] This continuous forging process not only completely eliminates centerline segregation in blooms, but also allows the centerline segregation ratio C/C_0 to be selected within the range of 0.7 to 1.0 as required by controlling the thickness of the unsolidified zone during reduction, which is accomplished by controlling the casting speed and the amount of reduction.[5]

Examples of the centerline segregation ratio of elements other than carbon in continuously forged blooms are shown in **Fig. 3**. These blooms were produced for bearing steel use with about 1.0% C and about 1.3% Cr, the chemical composition of which is shown in **Table 2**. For comparison, the blooms were obtained by the continuous forging process under two different forging conditions and by the conventional unforged process. In the continuously forged blooms, the negative segregation ratios of phosphorus and sulfur were higher than those of carbon, while the negative segregation ratios of silicon, manganese and chromium were practically equal to or a little lower than those of carbon. In other words, the elements that had high positive segregation ratios in the conventional bloom show high negative segregation ratios in the continuously forged blooms. It seems that this is because the molten steel, which is more concentrated than during forging, was discharged due to the fact that elements which are likely to segregate have lower equilibrium distribution coefficients,[10] which represent the ratio of the concentration in the solidified phase to the concentration in the unsolidified phase at the soldification front.

Table 2 Ladle analysis of high carbon chromium bearing steel (mass %)

Steel grade	C	Si	Mn	P	S	Cr
JIS SUJ2	0.99	0.23	0.40	0.018	0.004	1.36

By applying the continuous forging process, it is possible not only to completely eliminate centerline segregation, but also to select the optimum concentrations of elements in the central region of a product according to quality requirements. In addition, this process enables the phosphorus and sulfur concentrations in the central region to be lowered, these elements being considered harmful to forgeability and drawability, and the centerline segregation ratios of carbon, manganese and chromium to be controlled at levels close to 1.0, these elements being important for obtaining the required strength of a product.

3 Quality of Rod and Bar Products Made by the Continuous Forging Process

3.1 Improvement in the Drawability of High Carbon Steel Wire Rod

A high carbon steel bloom of the chemical composition shown in **Table 3** was continuously forged, and then rolled to a wire rod 5.5 mm in diameter from a 150-mm square billet rolled from the forged bloom. The wire rod was control-cooled on the Stelmor cooling conveyor. The microstructure of longitudinal sections of the wire rod thus produced and that of a wire rod produced from a conventionally forged bloom are shown in **Photo 2**. The wire rod from the continuously forged material does not show the centerline segregation that is apparent in the wire rod from the conventional material. In this case, the centerline segregation ratio of carbon was 0.90 in the wire rod from the continuously forged material, and 1.15 in the wire rod from the con-

Table 3 Ladle analysis of high carbon steel wire rods (mass %)

Steel grade	C	Si	Mn	P	S
JIS SWRH82A	0.83	0.19	0.50	0.010	0.007

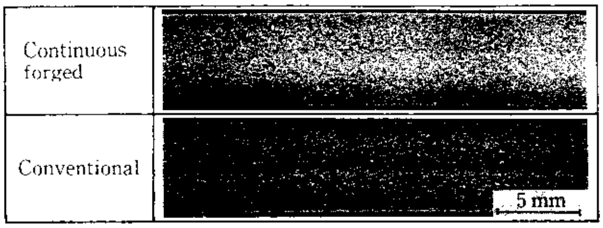


Photo 2 Macrostractures of 55 mmϕ wire rods (SWR H82A)

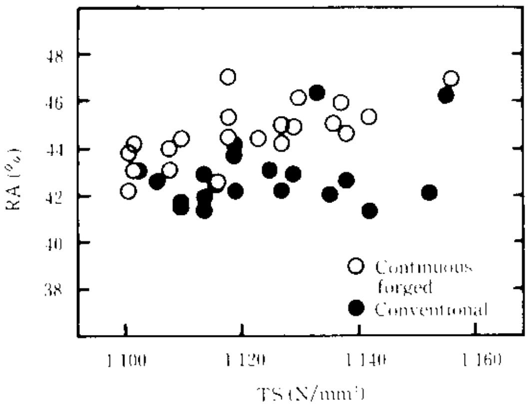


Fig. 4 Relationship between TS and RA of 5.5 mmϕ wire rods

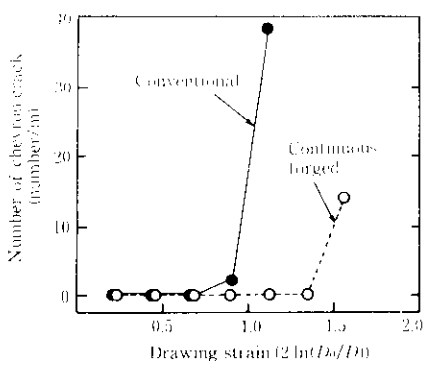


Fig. 5 Relationship between drawing strain and number of chevron-crack of 5.5 mmϕ wire

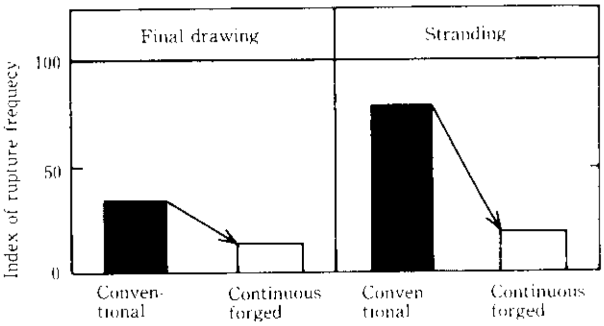


Fig. 6 Frequency of rupture at drawing process

ventional material.

The central region of the wire rod from the continuously forged material indicated negative segregation. As shown in **Fig. 4**, the wire rod from the continuously forged material exhibits no difference in tensile strength when compared with the wire rod from the conventional material, and is slightly superior in the reduction of area to the latter. To investigate drawability, a wire drawing experiment was conducted by setting the die approach angle at 25° to cause a wire break to occur easily. The number of chevron cracks[11] formed due to insufficient ductility in the region of center line segregation of the wire rod during drawing was measured from the changes in drawing load. As shown in **Fig. 5**, chevron cracks were formed in the wire from the continuously forged material in a higher drawability region than in the wire from the conventional material, the frequency of occurrence of chevron cracks being lower in the former than in the latter, while the former also outstanding in its wire drawing limit.[12] This seems to have been because the ductility of the central region of the wire from the continuously forged material was higher compared with that from the conventional material due to the existence of appropriate negative segregation in the central region of the former.

The results of a wire drawing test of this steel grade in production drawing equipment are shown in **Fig. 6**. It is apparent from this figure that the wire breakage ratio was substantially lowered by applying the continuous forging process.

3.2 Improvement in Rolling-Contract Fatigue Life of Bearing Steels

Factors that influence the high rolling-contact fatigue life required of bearing steels include centerline segregation and the cleanliness of the steel. **Photo 3** shows the cross-sectional macrostructure of an SUJ2 round bar rolled to 65-mm diameter from a 150-mm square billet produced from a cotninuously forged bloom. The centerline segregation ratio C_x/C_{0x} by X-ray diffraction for this SUJ2 round bar is shown in **Fig. 7**. In this case, C_{0x} and C_x represent the X-ray intensity in the 1/4 D region and the central region, respectively, of the round bar. The X-ray intensity was evaluated by the average value in a 2-mm square field of view. As shown in Photo 3, the centerline segregation that exists in the conventional material was eliminated by continuous forging, the centerline segregation ratio C_x/C_{0x} of carbon being about 0.95, thus indicating slightly negative segregation.

The technique for improving centerline segregation by low temperature casting described in Sec. 2.1, which involves a lower molten steel temperature in the tundish, is accompanied by the problem of decreased

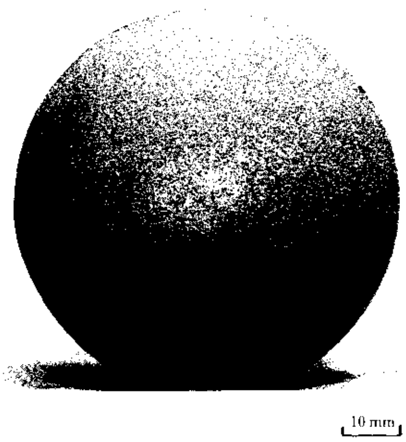


Photo 3 Macrostructure of continuous forged SUJ2 bar

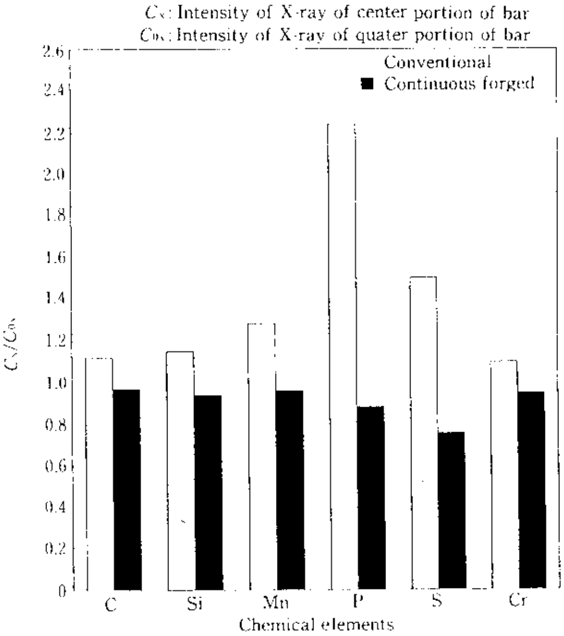


Fig. 7 Ratio of centerline segregation (C_x/C_{0x}) of SUJ2 bar (65 mmϕ)

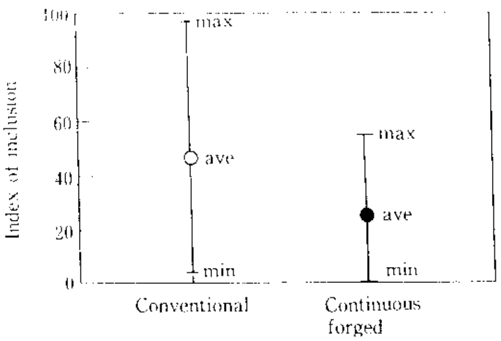


Fig. 8 Index of B-type inclusions at the center portion of 65-mmϕ SUJ2 bar (ASTM-A295 SAM method)

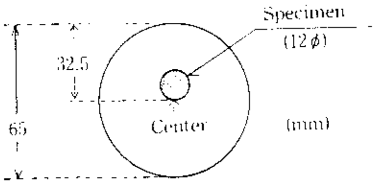


Fig. 9 Specimen taken from bar for rolling-contact fatigue life test

Table 4 Testing conditions of rolling-contact fatigue life test

Item	Value
Total load	3 599 N
Hertz maximum contact stress	5 884 N/mm^2
Rotating speed of the test specimen	46 240~46 800 cpm
Lubricating oil	#80 turbine oil

cleanliness of the steel. With the continuous forging process, however, it is possible to use a higher superheat of the molten steel in the tundish. An investigation was made into the cleanliness in the central region of a round bar made by continuous forging with 10°C higher superheating of the molten steel in the tundish compared with that for conventional material. This investigation was conducted according to the ASTM-A295 SAM method. The index of B-type inclusions (alumina-type inclusions) is shown in **Fig. 8**. It is apparent from this figure that the average index value of B-type inclusions in the bar from continuously forged material was about half that in the bar from conventionally forged material, and that the variation in the index of the former was also less.

It is apparent that the application of the continuous forging process resulted in the complete elimination of centerline segregation and an improvement in cleanliness. Therefore, specimens for a rolling-contact fatigue life test were taken from the central region of the round bar 12 mm in diameter shown in **Fig. 9** and were subjected to the usual heat treatment for bearing use. A rolling-contact fatigue life test was conducted on these specimens under the conditions shown in **Table 4** with the testing machine shown in **Fig. 10**. The rolling-contact fatigue life was evaluated by the number of cycles (L_{10}) at which 10% fatigue flaking occurred in the specimens used. As shown in **Fig. 11**, the rolling-contact fatigue life of the bar from continuously forged material was twice as long as the life of the bar from conventional material by continuously forging and using a 10°C higher degree of superheating of the molten steel in the tundish.

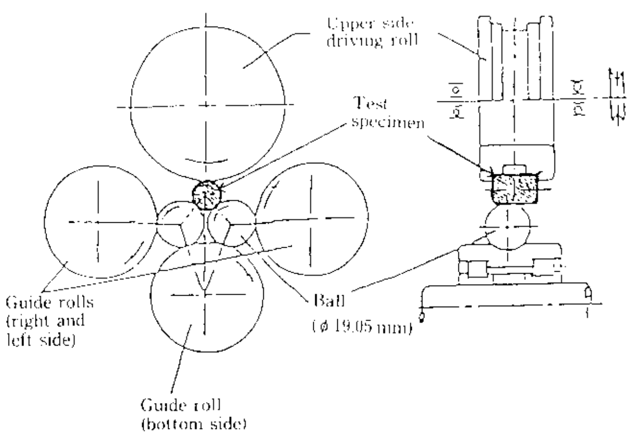


Fig. 10 Illustration of rolling-contact fatigue testing machine

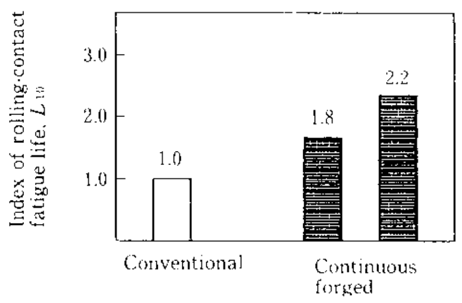


Fig. 11 Index of rolling-contact fatigue life, L_{10}, of SUJ2 bar

At present, the optimum conditions for continuous forging are being sought, and improvements to the continuous forging process are being made to further extend the rolling-fatigue contact life. Furthermore, the application of the continuous forging process to ball bearing steels is being examined; these steels have not previously been continuously cast by the conventional non-forged process due to the problem of centerline segregation, the ingot-casting process being used instead.

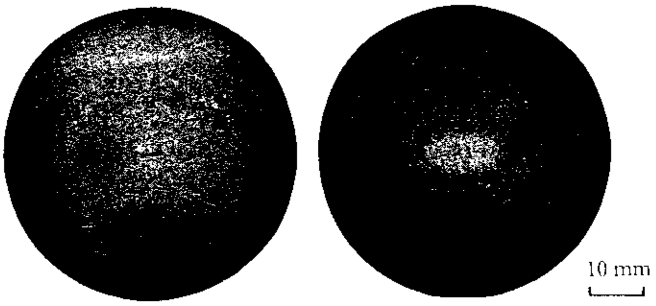
3.3 Improvement to Drilling in the Central Region of Carbon Steels for Machine Structural Use

Some rod and bar products are drilled through the central region. In conventional materials with centerline segregation, the life of drilling tools is short and the dimensional accuracy of drilled holes is low due to the shaky movement of the drill center.

A carbon steel for machine structural use with the composition shown in **Table 5** (S45C) was continuously forged and then rolled to a round bar 54 mm in diameter after producing a 150-mm square billet. A drilling test was conducted on the central region of the round bar. The macrostructure and centerline segregation ratio C/C_0 of the product are shown in **Photo 4** and **Fig. 12**, respectively, along with those for a round bar from conventional material. The centerline segregation ratios for carbon and sulfur were about 0.8 and 0.4, respectively.

Table 5 Ladle analysis of carbon steel for machine structural use (mass %)

Steel grade	C	Si	Mn	P	S
JIS S45C	0.44	0.24	0.79	0.017	0.015



Conventional Continuous forged

Photo 4 Macrostructures of S45C bar (54 mmφ)

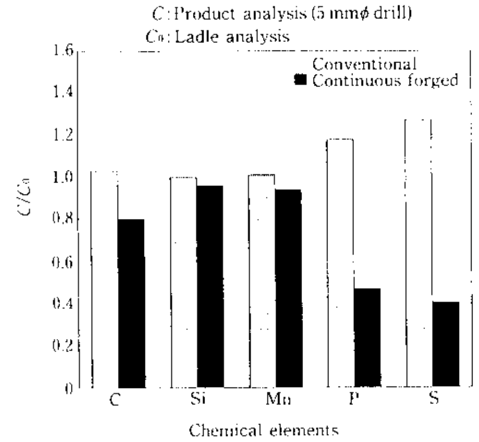


Fig. 12 Ratio of centerline segregation (C/C_0) of S45C bar (54 mmφ)

The results of the drilling test and the drilling conditions employed are shown in **Fig. 13**. The drill life was evaluated by the cumulative depth of drilled holes until drilling become impossible due to overheating or sticking of the drill.

In general, the hardness and sulfur content are important factors that determine the machinability of carbon steels; generally, the hardness of carbon steels is most affected by the carbon content, and the higher the sulfur content, the better the machinability. The centerline segregation ratio C/C_0 of carbon from the conventional material that was used as comparison in this test was about 1.0, and there was no extensive macrosegregation. Although C/C_0 of sulfur for the continuously forged material was as low as about 0.4, the drilling

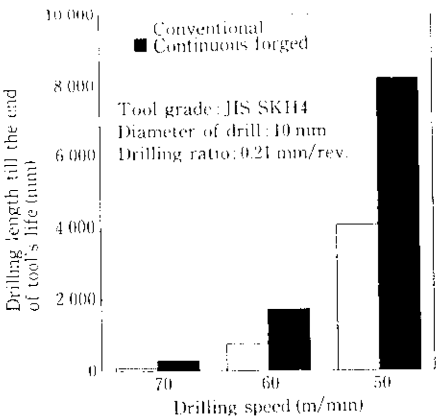


Fig. 13 Drilling length till the end of tool's life of S45C ar (54 mmϕ)

depth to the end of tool life in the continuously forged material was about twice that of the conventional material at all drilling speeds of 50, 60 and 70 m/min. This improvement in the ease of drilling through the central region of the 0.45% C steel seems to have been affected more by the carbon concentration than by the sulfur concentration in the central region; consequently, the decrease in hardness in the central region due to the reduced carbon concentration was effective for improving the ease of drilling through the material.

3.4 Other Improvements in Quality

The continuous forging process not only completely eliminates centerline segregation, but also makes appropriate selection of centerline concentration possible depending on secondary working process and quality requirements for final products. Furthermore, this process enables reduction of inclusions by raising superheat of molten steel in the tundish.

Other quality aspects capable of being improved by this process are shown below, and the effects of these quality improvements are being evaluated. A good reputation for quality has been gained among Kawasaki Steel's customers, and continuously forged materials have already been put into practical use for selected products.

(1) Improvements by the complete elimination of centerline segregation and the effective utilization of negative segregation:
  - Cracks caused by quenching
  - Unsuitable structure caused by friction welding

(2) Improvements by increasing cleanliness:
  - Fatigue life
  - Cold and warm forgeability

5 Conclusions

Kawasaki Steel's continuous forging process applies heavy reduction to a continuously cast bloom at the end of the solidification period to forcebly discharge the molten steel concentrated in the central region of the bloom. In June 1990, forging equipment was installed with the No. 3 continuous bloom caster at Mizushima Works.

An investigation was made into the quality of rod and bar products produced by the continuous forging process and the following results were obtained:

(1) Drawability was greatly improved by applying the continuous forging process to high carbon steel wire rods.

(2) When the process was applied to steels for bearing use, inclusions were decreased by raising the superheat of the molten steel in the tundish, and the rolling-contact fatigue life was extended.

(3) S45C carbon steel for machine structural use was produced with a centerline segregation ratio C/C_0 of about 0.8 and negative segregation was obtained by applying the continuous forging process. As a result, the ease of drilling in the central region was improved.

The continuous forging process not only permits the complete elimination of centerline segregation in blooms, but also enables the concentrations of elements in the central region to be selected appropriately as required. When this process is applied to the material for rod and bar products, it is possible not only to improve quality, but to omit heat treatment, inspection, etc. which have generally been required during secondary working. For this reason, the application of the continuous forging process can contribute greatly to reducing the cost of subsequent processing during secondary working.

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