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Improvement of Properties of Rods and Bars by Continuous Forging Process

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Improvement of Properties of Rods and Bars by Continuous Forging Process*

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Kawasaki Steel has developed a continuous forging process capable of producing rods and bars with neither center segregation nor center porocities. This method also makes it possible to control the center segregation ratio less than 1.0. The application of this method has improved a rolling-contact fatigue life of bearing steel, and has annihilated inner porocities of big size diameter bars made from continuously cast bloom. By utilizing the negative segregation obtained by this method, the carbon steel bars for machine structural use can be easily drilled at center portion due to a decrease in hardness. The alloy steel rods for machine structural use also can be drawn at high speed, and the high carbon steel rods can be processed without heat treatment due to an increase in drawability. This method makes it easier to increase tensile strength of final products by applying higher carbon steels.

1 Introduction

Almost all rod and bar products undergo forging, drawing, thermal refining, or other forms of secondary working before reaching the stage of final products. In the unlikely event that the base material contains a flaw, defects such as cracking or rupture will occur during these processes. In other words, secondary processing is equivalent to a full-length 100% inspection of rod and bar products. In recent years, as secondary working has become increasingly severe, the need to decrease the defect rate during processing has become extremely strong, therfore the quality requirements placed on steel material manufacturing have become markedly higher.

Two principal quality requirements are to produce a segregation-free center portion and to eliminate center porosity defects in continuously cast blooms for rod and bar products. A variety of improvement techniques have been used to achieve these goals, but a complete solution has not been achieved. For example, even though the defect ratio in final products was reduced using the conventional techniques, a zero defect rate was not realized, making it impossible to omit the inspection process for finished products. Moreover, deterioration in steel cleanliness and other collateral quality problems arose with conventional techniques, and it was not possible to respond adequately to the strict total quality requirements of rod and products.

Considering the limited room for improvement in the conventional techniques, Kawasaki Steel developed the continuous forging method, which applies continuous forging to blooms in the final stage of solidification,[1,2] and installed continuous forging equipment at Mizushima Works No. 3 Continuous Caster in June 1990.[3] This method not only solves the problem of centerline segregation and porosity defects in blooms, but also makes it possible to select the concentrations of chemical elements at center portion in response to product quality requirements by appropriately controlling forging conditions.[2,4-6]

This method has already reached the stage of practical use in some product applications, and customers have favorably evaluated the effect on quality improvement.[7-14] At present, the method is being applied in the ongoing development of rod and bar products with improved functions and higher added value.

This report describes the quality of wire rod products in which higher functionality and added value have become possible through the application of the continuous forging method.

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2 Conventional Methods of Alleviating Centerline Segregation and Continuous Forging Method

2.1 Problems for Product Quality Improvement When Conventional Techniques Are Applied

Techniques for alleviating centerline segregation and central porosities in continuously cast blooms include low-temperature casting[15] (by lowering the superheat of molten steel in the tundish), magnetic stirring in the mold or during solidification,[16,17] and low-speed casting.[17] However, in spite of their recognized effectiveness in alleviating centerline segregation and voids, none of these methods can at present be called adequate in perfectly solving these problems. Rather, these techniques in some cases have the side effect of deteriorating other aspects of product quality.

For example, low-temperature casting makes it difficult to float out non-metallic inclusions in the tundish because the viscosity of the molten steel in the tundish is increased. This has a negative impact on the cleanliness of the steel, reesulting in problems of rolling-contact fatigue life in products, and cannot be called an optimum method for steel grades which require high cleanliness.

Magnetic stirring causes negative segregation in stirred areas, which causes locally reduced hardness after quenching. For this reason, magnetic stirring cannot be applied to products in which cross-sectional uniformity of the quenching depth is critical. Moreover, low-speed casting reduces the surface temperature of the bloom when continuously cast blooms are unbended, making the bloom more susceptible to surface cracks during this process, and therefore is not necessarily an effective method for grades which are particularly sensitive to cracking at high temperature.

On the other hand, without reducing the degree of centerling segregation, it is possible to reduce the contents of P, S, and other elements by molten steel refining as a method of reducing the concentration of these impurities in the center portion. However, this method entails higher refining costs, and it cannot be used in applications where machinability is an important in secondary working requirement.

As suggested by the foregoing, the existing techniques for alleviating centerline segregation are not only inadequate for producing a segregation-free center portion, but have been found to have undesirable collateral effects on product quality, and therefore cannot be considered general-purpose techniques which fully meet the total quality requirements of high-grade rods and bars.

2.2 Product Quality Advantages with Continuous Forging Method

The continuous forging method uses anvils to apply heavy reduction to continuously cast blooms in the final period of solidification, extrudes the enriched molten steel in the central part of the bloom back upstream into the unsolidified section, and forcibly forms the final solidification point.[2] Past methods of improving centerline segregation did not expel the enriched molten steel, and were only capable of reducing the area of individual segregation portions attributable to this enriched material. In contrast, the continuous forging method makes it possible to produce completely segregation-free blooms.

Similarly, the conventional methods were only capable of reducing the size of individual voids created in the bloom center by contraction during solidification of the molten steel, and could not eliminate this problem, but in the continuous forging method, expulsion of the unsolidified molten steel completely prevents the formation of voids.

To summarize, continuous forging is capable of completely eliminating both centerline segregation and porosity defects, and does not cause the other types of quality degradation associated with the conventional methods. The continuous forging method is therefore a technology which fully answers the total quality requirements of wire and rod products.

For example, centerline segregation and cleanliness are factors which affect the long rolling-contact fatigue life required of bearing steels. Because centerline segregation can be completely eliminated with the continuous forging method, it is not necessary to apply low-temperature casting, which is accompanied by deteriorated steel cleanliness, and it is possible to increase the superheat of the molten steel in the tundish to a higher level than with conventional materials. As a result, the degree of cleanliness improves, and it is possible to extend the rolling-contact life of the product.

Moreover, the continuous forging method is not only useful in eliminating segregation in the bloom center, but also makes it possible, as necessary, to select a degree of central segregation (C/C_0) with the range of 0.7–1.0 by controlling the casting speed and amount of reduction. An example is presented in **Fig. 1**, which shows the results when different levels of continuous forging were applied to a bearing-use steel with the ladle analysis values shown in **Table 1**. The degree of centerline segregation (C/C_0) in a conventional, non-continuously forged material are also shown. The degree of centerline segregation (C/C_0) was evaluated from analysis values (C) of samplings taken from the steel center with a 5-mm ϕ drill in comparison with ladle values (C_0).

It is characteristics of the concentration of elements at the center of continuously forged blooms that the degree of centerline segregation of P and S tends to be smaller than that of C, while the degree of centerline segregation of Si, Mn, and Cr is similar to or slightly greater than that of C. In other words, the degree of centerline segregation of elements present in relatively large quantity in conventional, non-forged material de-

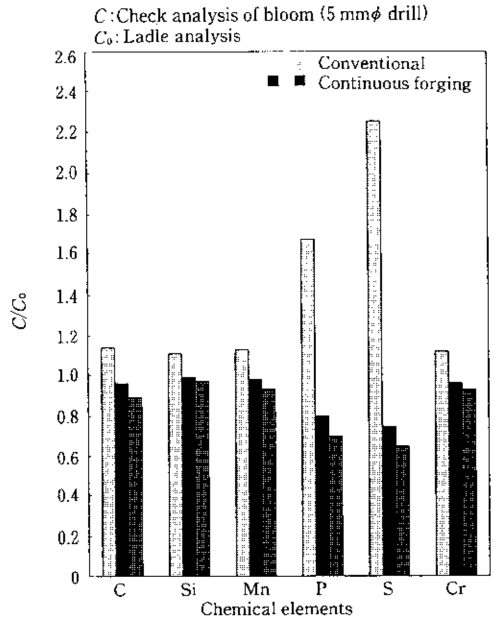


Fig. 1 Ratio of center line segregation (C/C_0) of SUJ2 bloom

Table 1 Ladle analysis of high carbon chromium steel for bearing use (mass%)

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

creases in continuously forged material. This is because, with elements which are more susceptible to segregation, there is a decrease in the equilibrium distribution coefficient of concentration in the solid phase at the solidification interface and enrichment in the unsolidified phase,[18] and consequently, more highly enriched steel is expelled during forging.

Thus, application of the continuous forging process is capable of producing products free of centerline segregation, but also makes it possible to select the composition of the product center to meet the quality requirements of rod and bar products. In addition, it is possible to lower the content of P and S at the center, which are recognized as having a detrimental effect on forgability, drawing performance, and sensitivity to bake cracking, and to control C, Si, Mn, and Cr, which are essential for securing the strength of final products, to a degree of central segregation approaching 1.0.

3 Quality of High-Function Rod and Bar Products with Continuous Forging

The previously mentioned effects of the continuous forging method and high-function items in rod and bar products produced by this method are shown in **Table 2**. Naturally, product quality is improved by eliminating centerline segregation (homogenization) and removing porosities, but improved ductility and reduced hardness of the center can also be obtained by securing negative centerline segregation. Making use of these features, higher functionality and higher added value become possible in rod and bar products.

The following presents examples of enhanced quality and higher functionality achieved by use of the continuous forging method, which is applied to 400 mm × 560 mm blooms. An appropriate casting speed and amount of forging are selected within the respective ranges of 0.40 m/min and 60–120 mm, depending on the steel grade and the degree of central segregation needed to meet quality requirements.

Table 2 Examples of improved properties of rods and bars by continuous forging process

Effects of continuous forging process		Examples of improved properties of rods and bars
Controlling chemical contents of center portion	Homogenizing	· Cancellation of hardness difference · No cracks caused by center segregation at quenching
	Negative segregation	· Drilling easily at center portion · Increasing drawing speed · Omitting heat treatment · Decreasing frequency of rupture at drawing · Increasing tensile strength by higher content of carbon
Annihilation of center porocity		· Decreasing inner deffects of big size diameter bar

3.1 Improved Rolling-Contact Fatigue Life of Bearing Steel

With the rod material used in steel balls for bearings, the segregated center portion of the steel is exposed to the ball surface (rolling surface). Centerline segregation is generally considered to have a negative effect on the rolling-contact fatigue life of bearings. As one cause of this problem, it is thought that the segregated center portion becomes harder than other parts of the material after quenching.

For this reason, it was formerly impossible to use

Table 3 Ladle analysis of high carbon chromium steel for ball use of bearing (mass%)

Steel grade	C	Si	Mn	P	S	Cr
JIS SUJ2	0.99	0.26	0.40	0.017	0.003	1.34

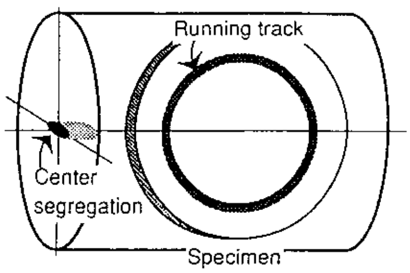


Fig. 2 Sampling position of test piece

Table 4 Chemical analysis of center portion of bars (5 mmϕ drill) (mass%)

	C	Si	Mn	P	S	Cr
Continuous forging	0.91	0.25	0.39	0.012	0.002	1.28
Conventional	1.05	0.26	0.41	0.019	0.004	1.36

Table 5 Testing conditions of rolling-contact fatigue life test

Item	Value
Size of contacting ball	9.525 mmϕ
Hertz maximum contact stress	5 260 N/mm^2
Rotating speed	1 800 cpm
Lubricatig oil	#68 Turbine oil

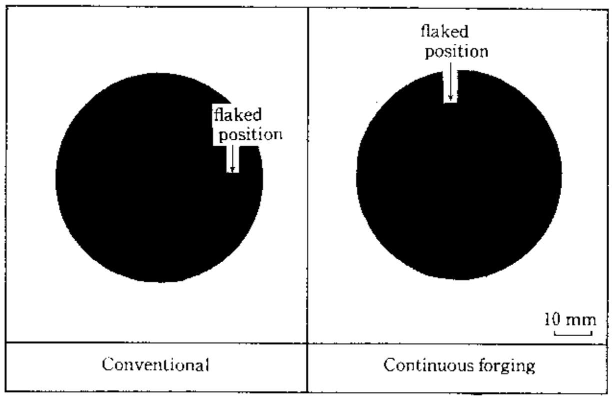


Photo 1 Macrostructure of test specimen after rolling-contact fatigue life test

continuously cast steel as rod material for bearing balls. Instead, material was produced using ingot casting with small molds, which caused a less significant degree of centerline segregation.

On the other hand, the continuous forging process makes it possible to prevent higher hardness by eliminating centerline segregation.

With the aim of using continuously cast materials in bearing balls, continuous forging was applied to a steel grade having the chemical composition shown in **Table 3**. Products made from this steel were subjected to a rolling-contact fatigue test, and the results were studied.[19,20]

Test pieces are produced by rolling continuously-forged blooms into round bars, followed by cutting as shown in **Fig. 2** to expose lines in the segregated center portion of the steel material at the surface of the test pieces. Then, the heat treatment normally given in bearing applications was applied, and lapping polishing was performed. A check analysis of the bars used in this test was made after sampling with a 5-mmϕ drill. The analysis results are shown in **Table 4**. Centerline segregation was found in the conventional material, and slight negative segregation was found in the continuously forged material, which showed a degree of centerline segregation (C/C_0) of 0.92 for C.

A point-contact rolling-contact fatigue test was then performed under the conditions given in **Table 5**. The macrostructure of specimens after the test is shown in

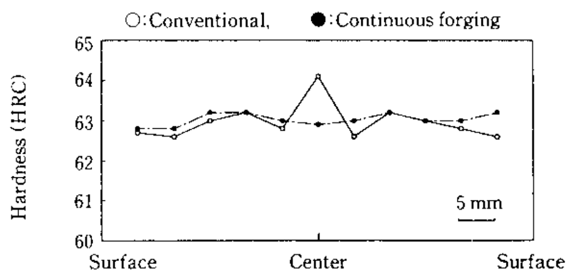


Fig. 3 Hardness distribution of specimen at rolling-contact fatigue life test

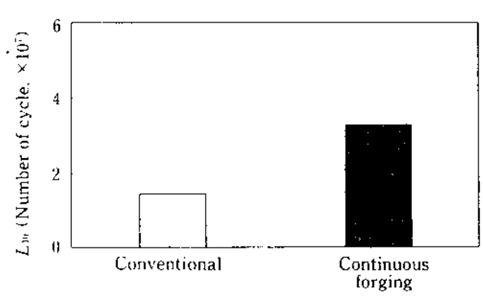


Fig. 4 Rolling-contact fatigue life (L_{10})

Photo 1; hardness distributions are shown in **Fig. 3**. Rolling-contact fatigue life and the rate of flaking near the centerline of the round bars are shown in **Figs. 4**

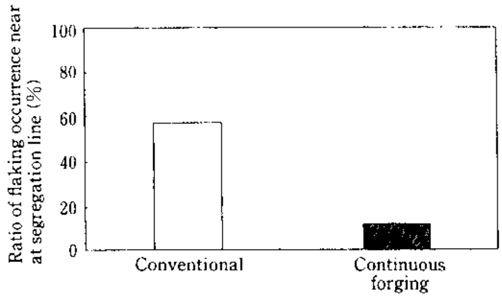


Fig. 5 Ratio of flaking occurrence near at center segregation line

and **5**, respectively. Rolling-contact fatigue life L_{10} was defined as the number of cycles at which 10% fatigue flaking occurred in the rolling-contact fatigue test among the total number of specimens.

As shown in Fig. 3, the hardness of the center portion of the continuously forged material, and was substantially the same as the hardness of other parts of the material. It was also found that the fatigue life (L_{10}) of the continuously-forged materials was approximately three times longer than that of the conventional material. As shown in Fig. 5, this was attributed to the reduced rate of rolling-contact fatigue flaking at the central segregation line, which is illustrated in Photo 1.

The results described above demonstrate that it is possible to produce rod materials for use in the steel balls of ball bearings by applying the continuous forging method, because this method is capable of reducing the ratio of the rolling-contact flaking originating in centerline segregation.

3.2 Improved Drilling Performance in Center of Carbon Steel Rods and Bars

With some rod and bar products such as steels for nut use, the product center must be drilled out. The excessively hard center of materials, which in the past were found to have centerline segregation, caused problems such as short drill life and poor dimensional accuracy in drilled holes due to drill-center deviations.

A center area drilling test was conducted by using carbon steel S 45 C for machine structural use, which was produced by the continuous forging method and rolled into round bars of 54 mmϕ. The chemical composition of the steel is shown in **Table 6**. The degree of centerline segregation (C/C_0) of the round bars is shown in **Fig. 6**, and their cross-sectional hardness distribution **Fig. 7**.

Table 6 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

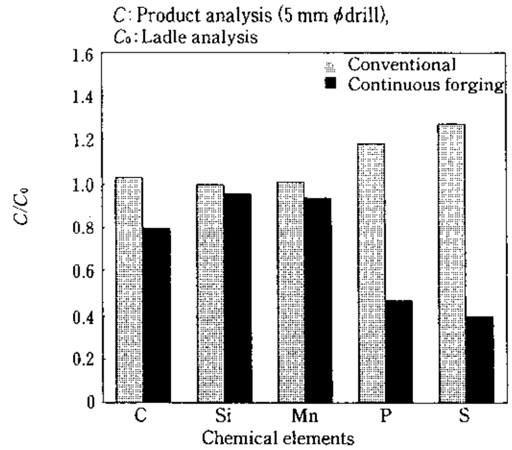


Fig. 6 Ratio of center line segregation (C/C_0) of S45C bar (54 mmϕ)

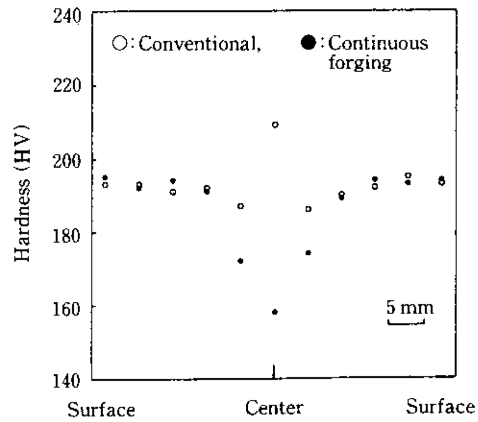


Fig. 7 Hardness distribution of the cross section of S45C bar (54 mmϕ)

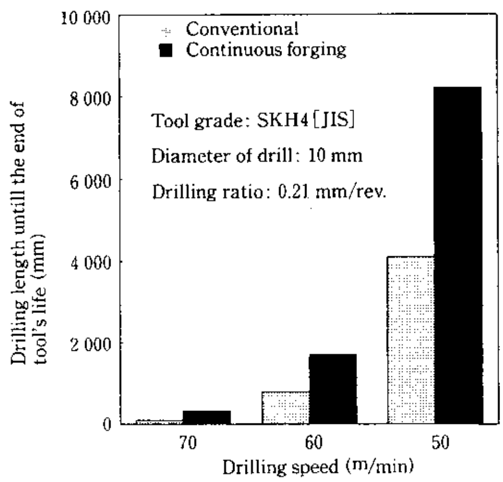


Fig. 8 Drilling length untill the end of tool's life (S45C bar 54 mmϕ)

Figure 8 shows the results of a drilling test. Tool life was evaluated by the total length drilled until drilling become impossible due to overheating or sticking. At all the drilling speeds tested, viz. 50, 60, and 70 m/min, the total drilled length in the center of continuously forged materials was improved to approximately double that with conventional materials.

Generally, the principal factors which determine machinability of carbon steels are hardness and S content. Low hardness and high S content are favorable for cuttability. The degree of central S segregation in the center portion of the present material was low at 0.4, but the effect of the decrease in hardness is considered to outweigh this factor, resulting in improved drilling performance.

3.3 Increase of Drawing Speed in Alloy Steel Rod Material

In the cross-section of rod materials, stress shows its maximum at the center portion of the material during drawing, while the center portion shows the minimum value for ductility if centerline segregation is present. For this reason, breakage attributable to centerline segregation may occur during drawing. However, the ductility of this region can be improved by using the continuous forging process to obtain negative segregation in the center portion. Negative segregation substantially decreases the frequency of breakage,[7] and should also make it possible to increase the drawing speed. Kawasaki Steel produces direct softening alloy steel rod material[21,22] by controlled rolling, which allows the customer to omit the annealing process, but when the drawing speed is increased, breakage has occurred even with this material because centerline segregation is high locally, and because a bainite structure having lower ductility than ferrite or pearlite is formed in areas where the cooling speed after rolling is high.

Table 7 Ladle analysis of chromium molybdenum steel for structural use (mass%)

Steel grade	C	Si	Mn	P	S	Cr	Mo
JIS SCM420	0.22	0.25	0.75	0.015	0.007	1.10	0.19

In an effort to solve these problems, continuous forging was applied to blooms with the chemical composition shown in **Table 7**. The material was rolled to 5.5 mmϕ using the necessary controlled rolling for direct softening treatment. The degree of centerline segregation (C/C_0) was investigated and found to be 0.91. **Photo 2** shows the macro- and microstructures at the quarter and center portions of the material. Because the centerline segregation is negative and the C concentration is low in the continuously forged material, not only is no bainite structure observable in the center, but a reduced amount of pealite in the center can also be confirmed. Drawing this material from 5.5 mmϕ to 4.0 mmϕ did not cause breakage, and as can be seen in **Fig. 9**, the index of drawing speed was 1.6 times greater

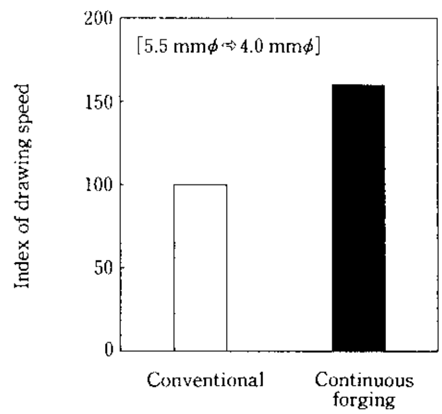


Fig. 9 Index of drawing speed of SCM420 rods (5.5 mmϕ)

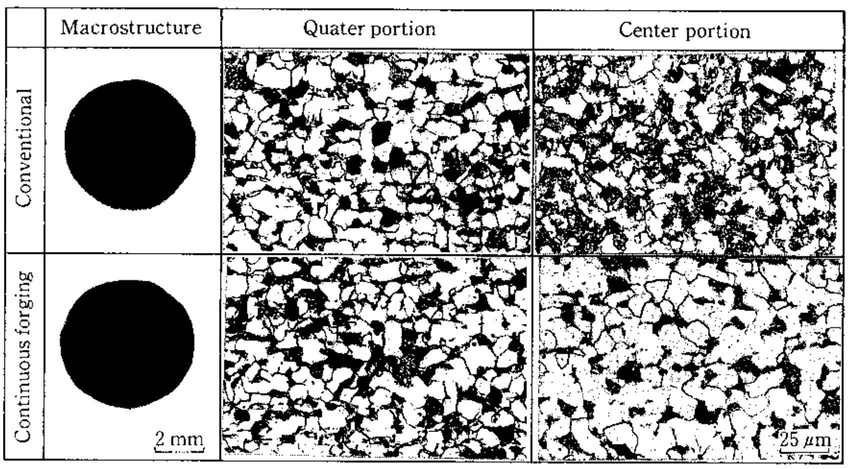


Photo 2 Macrostructure and microstructure of SCM420 rods

than with the conventional material.

3.4 Increased Ductility in High Carbon Steel Rods

Both strength and ductility are required in final products produced by drawing high carbon steel rods. Conventional rods with centerline segregation not only show low ductility in the center portion, but also exhibit internal porosity defects occurring during drawing.[23] These problems make heat treatment (wire lead patenting, etc.) indispensable, either before or during drawing, in applications where it was necessary to secure ductility after drawing.

Continuous forging was therefore applied to blooms for high carbon steel rod use. The ladle-analysis composition and actual composition of the center portion of the forged blooms is shown in **Table 8**. After rolling 11 mmϕ rods, the material was drawn to 4.2 mmϕ. The elongation and drawing values after drawing, omitting lead patenting, are shown in **Fig. 10**, in comparison with a conventional material to which lead patenting was applied.

The ductility and drawability of continuously forged materials, even omitting wire lead patenting, is superior to that of conventional wire lead patented materials. Accordingly, because use of the continuous forging method to produce negative segregation makes it possible to increase material ductility, it is considered possible for customers to omit lead patenting and similar treatment processes with continuously forged products.

Table 8 Analysis of ladle and center portion of bloom of high carbon steel rods (mass%)

	C	Si	Mn	P	S
Ladle analysis	0.81	0.25	0.81	0.017	0.008
Center portion of bloom	0.71	0.24	0.78	0.012	0.005

Steel grade : JIS SWRS82B, 5mmϕ drill

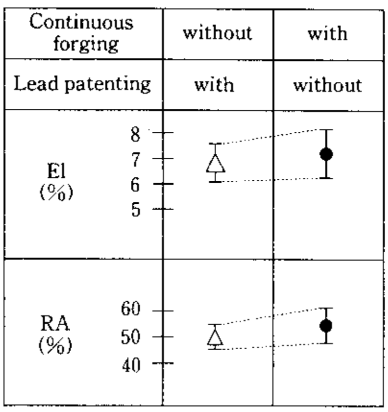


Fig. 10 El and RA of drawn wire rod

3.5 Higher Strength Obtained by Adoption of Higher Carbon Contents

As a means of securing high strength in final products, it is possible to adopt a higher carbon content, but this is not necessarily a practical alternative because, if centerline segregation exists, the carbon content at the center portion will be excessive and breakage during working and other problems may occur. For example, with high-carbon steel rods having a carbon content on the order of 0.7–0.8%, if higher carbon contents are adopted in order to secure higher strength, proeutectoid cementite will precipitate at the center portion, where the cooling rate is the slowest of all part of the bar cross-section. This proeutectoid cementite is markedly lower in ductility than other parts of the material structure, and may cause breakage during drawing. Moreover, even if the bar does not actually separate, it is difficult to apply such material to critical safety parts requiring high reliability because the drawing process produces porosities at the center of rod.

However, if negative centerline segregation is obtained by continuous forging, it is possible to prevent the precipitation of proeutectoid cementite at the center portion, even at elevated carbon contents. Thus, the continuous forging process is an easy, practical method of increasing the carbon content in high-strength products.

An example is shown in **Tabel 9**. Although in the past 0.77% C material was used for practical use in view of the proeutectoid cementite problem, practical use of 0.87% C material is possible by applying the continuous forging method. As a result, the strength of the final product can be increased from 1 900 N/mm^2 to 2 000 N/mm^2 simply by adopting a high carbon composition.

This material is used in springs for automobile brakes and has won a favorable response from customers for the increased resistance to permanent settling in fatigue, which are possible due to the higher strength of the product.

Table 9 Chemical composition of high carbon steel rods for spring use and their tensile strength of final products

Process	Steel grade (JIS)	Chemical analysis (mass%)					Tensile strength (N/mm^2)
		C	Si	Mn	P	S	
Conventional	SWRS77B	0.77	0.22	0.75	0.011	0.005	1 900
Improved	SWRS87A	0.86	0.21	0.44	0.010	0.005	2 000

3.6 Continuous Casting of Large Diameter Round Bar

The solidification and contraction of billets causes porosities at the billet center. Conventional techniques can reduce the size of these porosities, but cannot eliminate them completely. On the other hand, it is possible to pressure bond, that is, press porosities closed by rolling. This effect is found with higher rolling temperature, slower rolling speeds, and similar conditions, but cannot be fully realized in rolling large-diameter round bars because it is not possible to increase the forging ratio.

In products where central porosities would be a problem in large-diameter round bars during working or in the final product after working, it has therefore been necessary to produce the product from ingots with a larger cross section than is available with continuously cast billets in order to increase the forging ratio during rolling. For example, with large diameter bar for large beaing race use (an example of composition is shown in **Table 10**), the forging applied to the product is liable to expose porosities in the center portion of the material at the inner surface of the bearing race and cause inner surface flaws.

Photo 3 shows the macrostructure of SUJ3, 250 mmϕ (forging ratio: 4.6) for use in bearing races. The specimens were produced from conventional continuously-cast materials with and without continuous forging. **Figure 11** shows the index of residual inner defects as determined by ultrasonic testing applied under the UST conditions shown in **Table 11**.

Table 10 Ladle analysis of high carbon chromium steel for race use of bearing (mass%)

Steel grade	C	Si	Mn	P	S	Cr
JIS SUJ3	0.96	0.64	1.09	0.015	0.004	1.10

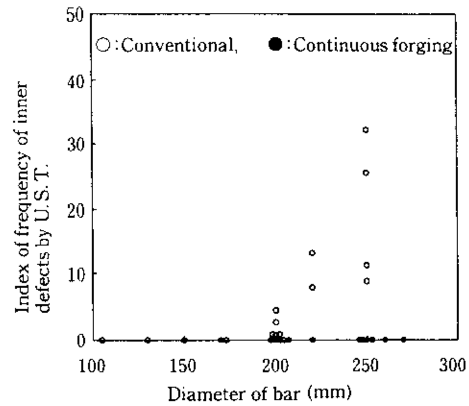
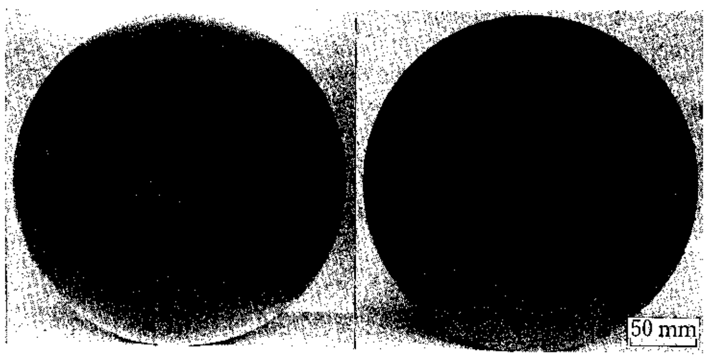


Fig. 11 Effect of diameter of bars on inner defects by continuous forging process (size of cast bloom: 400 × 560 mm)

Table 11 Conditions of ultrasonic test (UST) of inner defects for big size diameter bars

Item	Value
Frequency	5 MHz
Size of probe	20 mmϕ
Sensitivity	STV-G V 15−1.4=70%
Disregard level	<30%

The continuous forging method not only eliminates centerline segregation, but is also capable of closing voids in the material center at the stage of bloom solidification, thereby eliminating the problem of inner defects in blooms, even for large-diameter round bars, which have a small forging ratio. Thus, the continuous forging process makes it possible to apply continuously-cast materials to the production of large-diameter round bars.



Conventional　　Continuous forging

Photo 3 Macrostructure of big size diameter bar (250 mmϕ)

4 Conclusions

The continuous forging process applies heavy continuous reduction to blooms in the final stage of solidification during continuous casting. The process was developed by Kawasaki Steel and realized in June 1990 in a commercial forge constructed at Mizushima Works No. 3 Continuous Caster. The method not only is capable of eliminating centerline segregation and inner defects in blooms, but also makes it possible to select the level of concentration of chemical elements at the bloom center in response to product quality requirements by controlling forging conditions.

Findings in an investigation of the quality of rod and bar products produced with the continuous forging process are as follows:

(1) In high-carbon chromium steels for bearing use, it was found that rolling-contact fatigue life increased from that in conventional materials. This was considered attributable to the fact that it was possible to eliminate centerline segregation.

(2) In carbon steel S45C for machine structural use, the hardness of the center portion was reduced by producing negative segregation in the bloom center, which resulted in improved drilling performance at the product center.

(3) In alloy steel SCM 420 for machine structural use, negative segregation at the center improved central ductility, making it possible to increase the drawing speed.

(4) In high carbon steel rod material, negative centerline segregation improved ductility after drawing to the same level of the conventional wire after lead patenting treatment. This suggests that the continuously forged materials will allow customer to eliminate lead patenting or similar heat treatment processes.

(5) Negative segregation in the center portion not only eliminates centerline segregation, but also improves the ductility of this region; the continuous forging process therefore has greater potential than other methods in the practical application of enhanced carbon content to secure higher strength in high carbon steel.

(6) In large-diameter round bars, which have a small forging ratio, the continuous forging process is able to close centerline porosity defects at the cast-bloom stage, eliminating the need to close these voids by the conventional method of increasing the forging forming ratio (e.g., making size of bloom larger), and thereby making it possible to manufacture large-diameter bars by the continuous casting route.

As described above, the continuous forging process not only improves the quality of rod and bar products, but also makes it possible to improve the productivity of customers' operations and omit the heat treatment and inspections which have conventionally been necessary during or after working. Accordingly, the continuous forging process can make an important contribution to reducing customer costs.

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