KAWASAKI STEEL TECHNICAL REPORT
No.26 (June 1992)
Artificial Intelligence and Wire Rods and Steel Bars

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The body can be viewed from the next page.

Development of Thermomechanically Control-Processed High Carbon Chromium Steels for Ball Bearing without Annealing*


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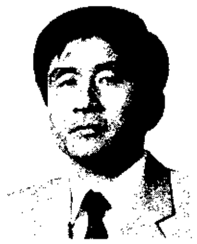
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Synopsis:

High carbon chromium steels such as JIS SUJ2 for ball bearings have very high hardness under conventional hot-rolled conditions. Thus, these steels need soft-annealing treatments before undergoing cold forming such as saw cutting and cold shearing. However, these heat treatments, which need reheating at 700~800°C for several hours followed by slow cooling, incur high cost and produce low quality. Therefore, techniques for producing large diameter steel bars without soft-annealing process have been studied in the laboratory scale by applying the thermo-mechanical control process (TMCP).

Low-temperature reheating and low-temperature rolling have accelerated transformation of austenite into pearlite, refined cementite plates and improved mechanical properties of as-rolled and/or spheroidized steels.

1 Introduction

High-carbon chromium steels for ball bearing, as represented by JIS SUJ2, are widely used as materials for bearing components. In recent years, particularly from the expansion of the automobile, construction machinery, electrical machinery and other indutries, the demand for these steels has increased rapidly.[1] In terms of quality, the performance requirements for higher speed, greater load-carrying capacity, miniaturization, and higher temperature have progressively become severer.[2] To meet these requirements, steel-makers supply steel products with clean and stable material quality by reducing nonmetallic inclusions and maintaining rigid quality control in all the processes from casting to rolling by making the most of the latest steel-making techniques.[3] Furthermore, rapid improvement has been made in the rolling contact fatigue of bearings due to higher precision in the working and manufacturing techniques used by the bearing manufacturers.[4]

With ball bearing steels, the essential features of hardness and toughness greatly hinder productivity at the secondary working stage, in which the material is worked into bearing components with the required characteristics. In other words, because of their chemical composition, ball bearing steels have very high hardness in the as-hot-rolled condition that results from the usual manufacturing process. As a result, the material preparation stage presents difficulties in terms of tool life and productivity. In the normal case, therefore, softening annealing is usually done to reduce the hardness before such cold working operations as sawing and shearing. Because this annealing generally requires reheating at 700 to 800°C for many hours and subsequent slow cooling, the degree of decarburization is high

* Originally published in *Kawasaki Steel Giho*, 23(1991)2, 98-104

and scale loss is large; in addition, the annealing process involves high heat treament cost and a long manufacturing period. For these reasons, much attention is being paid to this annealing process in an attempt to reduce manufacturing costs.

Therefore, if high-carbon chromium steels for ball bearings can be developed that permit cold working such as sawing and shearing in the as-hot-rolled condition, they would offer great advantages to the secondary working manufacturers by reducing the heat treatment cost, and shortening the manufacturing time.

Although an examination and subsequent development of such alloy steels as SCM435 has been conducted for steels that permit such working as wire drawing and cold forging in the as-hot-rolled condition,[5] there have been few reports on high-carbon chromium steels for ball bearings. In this study, therefore, the authors examined the feasibility of omitting the softening annealing process (i.e., the possibility of direct softening) by applying the thermomechanical control process (TMCP),[6-8] which is widely used in producing as steel plates for shipbuilding, to high-carbon chromium steels for ball bearings. Laboratory experiments were used to examine austenite (γ) recrystallization, pearlite transformation and cementite precipitation.[9,10]

2 Concept for Omitting the Softening Annealing Process to Produce High-Carbon Chromium Steels for Ball Bearings

High-carbon chromium steels for ball bearings usually have a hard structure composed of proeutectoid cementite and pearlite in the as-hot-rolled condition. The basic method for softening this structure, therefore, is to control the precipitated shape of the cementite and ferrite constituting lamellar pearlite and the grain size of the pearlite structure.

The strength of the pearlite structure depends generally on the size of the pearlite grains, the pearlite lamellar spacing, and the strength of the ferrite matrix,[11] being particularly influenced by the lamellar spacing. To reduce the strength, therefore, it is necessary to widen the lamellar spacing in the stage of pearlite transformation from the hot-rolled austenite phase. The following methods are conceivable for this purpose:

(1) Many nucleation sites for pearlite transformation can be formed by refining the γ grains by TMCP, so that transformation can start at as high a temperature as possible and in the shortest time.

(2) The cooling rate and transformation rate can be sufficiently reduced so that the transformation temperature can be held at the highest possible level to obtain a sufficiently wide lamellar spacing.

It would be possible to reduce the hardness of the material by these methods. However, even if improvements are made in the workability for cold shearing, sawing, etc. during the secondary working process, this is pointless if the required quality of the finished product in terms of the depth of hardening, quench hardness and rolling contact fatigue are impaired in the tertiary and subsequent working processes.

Accordingly, it is necessary to improve cold workability during the secondary working stage without impairing the quality of the finished products. A laboratory experiment was conducted on the transformation behavior and rolling to determine (1) cooling rate after hot rolling required for direct softening, (2) the contribution of hot working to γ grain recrystallization and the acceleration of pearlite transformation, and (3) the effect of rolling conditions on mechanical properties and microstructure when assuming multipass rolling in commercial production.

3 Experimental Method

3.1 Steel Sample

The chemical composition of the steel used in the experiments is shown in **Table 1**. This was in the form of a commercial steel bar 110 mm in diameter obtained by hot rolling a bloom produced by using a converter and CC equipment. This steel was SUJ2 high-carbon chromium steel for ball bearings in accordance with JIS.

Table 1 Chemical composition of steel used (wt. %)

Grade	C	Si	Mn	P	S	Cr
SUJ2	0.98	0.25	0.40	0.017	0.007	1.34

3.2 Heating and Cooling Conditions Necessary for Omitting Softening Annealing

An experiment was conduced in which the reheating temperature, cooling rate and slow-cooling starting temperature were varied to determine the cooling rate after hot rolling that was necessary for direct softening and to minimize the treatment time. A specimen 5 mm in diameter and 8 mm long was heat treated under the conditions shown in **Fig. 1**, using a fully automatic dilatometer (Formastor F).

3.3 Effect of Hot Working on γ Grain Recrystallization and Precipitation of Proeutectoid Cementite

To evaluate the contribution of hot working to grain refinement in the γ grain recrystallization process and to the acceleration of pearlite transformation, an investigation was made to study how the γ grain recrystallization and precipitation behavior of proeutectoid cementite would be affected by various reheating temperatures, working temperatures and degrees of deformation. A specimen 8 mm in diameter and 12 mm long was deformed at a mean strain rate of 0.18/s representato the middle of the side of each slab.

Observation of the microstructure, proeutectoid cementite and γ grains, hardness, and tensile strength were conducted for each specimen after heat treatment and rolling. The mechanical properties and microstructure were also examined after spheroidizing annealing.

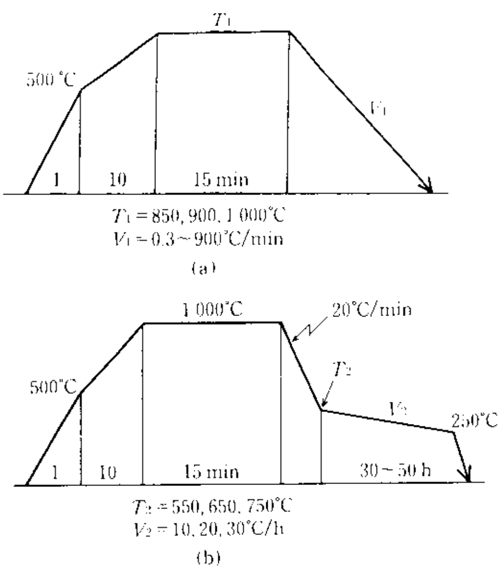

Fig. 1 Pattern of heat treatment

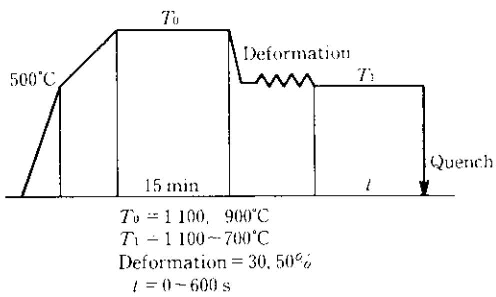

Fig. 2 Deformation and heat treatment condition

tive of hot rolling, and then cooled under the conditions shown in **Fig. 2**, using the fully automatic dilatometer.

3.4 Effect of TMCP with a Laboratory Rolling Mill on the Mechanical Properties

To investigate the effect of TMCP by multipass rolling on the mechanical properties and microstructure, rolling experiments were conducted under various reheating and rolling conditions on the basis that these conditions could be applied to the commercial production of high-carbon chromium steels for ball bearings. Slabs for this experimental rolling 70 mm in thickness, 50 mm in width and 200 mm in length were reheated to 1 250°C and 950°C. They were then reduced to a thickness of 12 mm in six passes at a reduction of 25.5%/pass at various rolling temperatures. After that, they were cooled by water, air or by using a heat insulating material of ceramic fiber. The cooling rate was about 50°C/s with water, about 0.6°C/s with air, and about 0.06°C/s with insulation.

To control the rolling temperature, measurements were taken by a chromel-alumel thermocouple attached to the middle of the side of each slab.

4 Experiment Results

4.1 Heating and Cooling Conditions Necessary for Omitting Softening Annealing

The effects on handness of the reheating temperature and cooling rate defined in Fig. 1 (a) are shown in **Fig. 3**. The effects on hardness of the cooling starting temperature and slow-cooling rate defined in Fig. 1 (b) are shown in **Fig. 4**. The microstructures obtained under the conditions given in Fig. 1 (b) are shown in **Photo 1**. The following are evident from Figs. 3 and 4:

(1) In both the temperature range of 850 to 1 000°C and the range of 550 to 750°C, the hardness decreased with decreasing cooling rate. In this case, the hardness had a good linear correlation with the logarithm of the cooling rate.

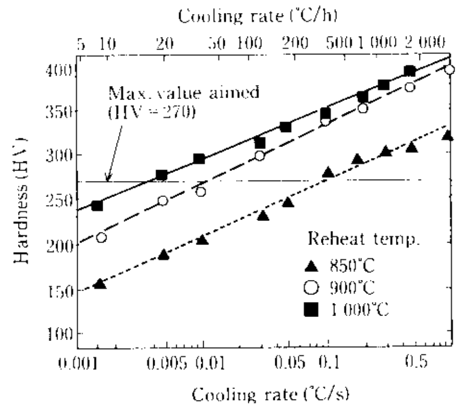

Fig. 3 Effects of heating temperature and cooling rate on hardness

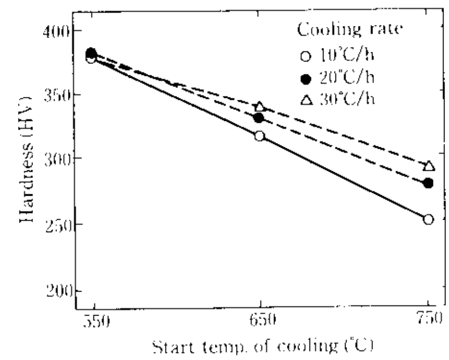

Fig. 4 Effects of starting temperature and cooling rate of slow cooling on hardness

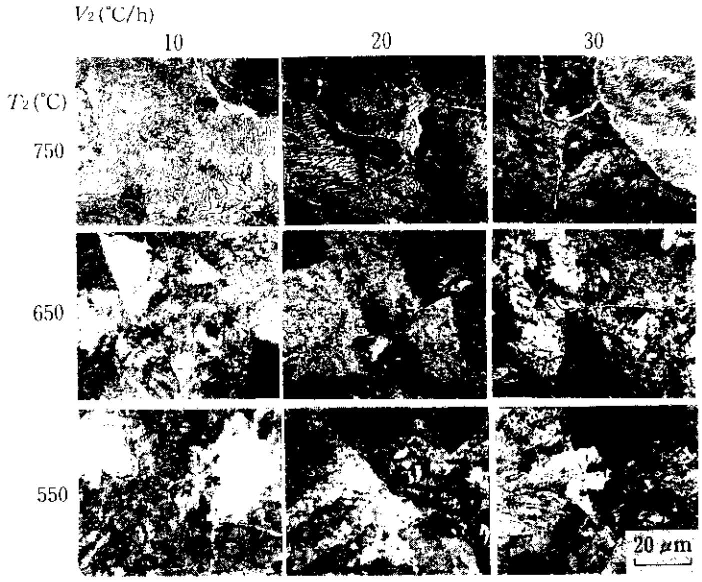

Photo 1 Effects of cooling rate and starting temperature of slow-cooling (see Fig. 1(b)) on microstructures and cementite networks

(2) The critical cooling rate to obtain a Vickers hardness of HV $\leqq$ 270 or a Brinell hardness HB $\leqq$ 102, at which cold cutting is considered possible without problems, was 0.05°C/s or less for a reheating temperature of 1 000°C, and 0.1°C/s or less for 850°C. It may be said that lowering the austenitizing temperature will heighten the critical cooling rate necessary for obtaining soft steel.

(3) Concerning the effect of the cooling starting temperature, it was found that a sufficiently low level of hardness could be obtained when slow cooling was started at 800°C and 750°C, which are both above the pearlite transformation point of 730°C, while at 650°C and 550°C, which are below the pearlite transformation point, the effect of softening was small even if the slow cooling rate was reduced.

(4) Concerning the precipitation of proeutectoid cementite, thick plate-like precipitates were observed when the cooling starting temperature was 750°C, which is above the pearlite transformation point. In particular, the lower the slow cooling rate, the more remarkable was the growth of proeutectoid cementite. On the other hand, there were relatively few precipitates when the cooling starting temperature was 650°C and 550°C, which are both below the pearlite transformation point. This suggests that the lower the cooling rate in the cementite transformation temperature range, the more marked would be the precipitation of proeutectoid cementite.

As already mentioned, softening could be accomplished by the combination of low-temperature reheating, high-temperature finishing and final slow cooling. However, the precipitation of proeutectoid was apparent. Therefore, ductility may deteriorate and the fatigue property may be impaired by the worse shape of spheroidal carbides after spheroidizing annealing.

4.2 Effect of Hot Working on γ Grain Recrystallization and Precipitation of Proeutectoid Cementite

Photo 2 shows an example of the recrystallization behavior of γ grains and the precipitation of proeutectoid cementite when hot working was conducted under the conditions shown in Fig. 2. **Figure 5** shows the relationship between the hardness and deformation temperature when the temperature was not held after deformation and the specimen was cooled at 0.1°C/s, with the other conditions of Fig. 2 remaining unchanged.

(1) With the material reheated to 1 100°C and deformed at 1 000°C, the γ grains recrystallized immediately after deformation and, therefore, the temperature of 1 000°C is in the γ region in which recrystallization is easy. With the material reheated at 1 100°C and deformed at 800°C, the γ grains were elongated in the direction of deformation, and band-like structures considered to be deformation bands or annealing twins[12] were observed inside the elongated grains. Furthermore, many very fine recrystallized grains were observed at the γ grain boundaries, and it is apparent from this that this temperature range is in the γ region for unrecrystallized to partially recrystallized grains.

(2) With the material deformed at 800°C and not held for any time, the precipitation of proeutectoid cementite scarcely proceeded. With the material deformed at 800°C and held for 600 s, precipitation of proeutectoid cementite was observed along the elongated γ grain boundaries and deformation bands. However, at this point of time, recrystallization of the γ grains in the same place was complete.

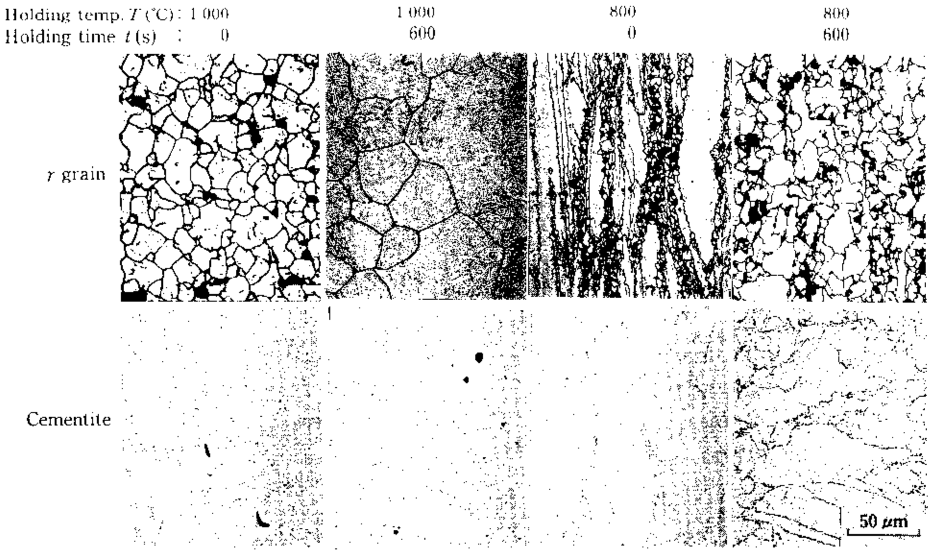

Photo 2 Effects of holding temperature and time after 50% reduction of samples reheated at 1 100°C on γ grain recrystallization and cementite precipitation (see Fig. 2) (γ grain, saturated picral etch; cementite, NaOH-picric acid etch)

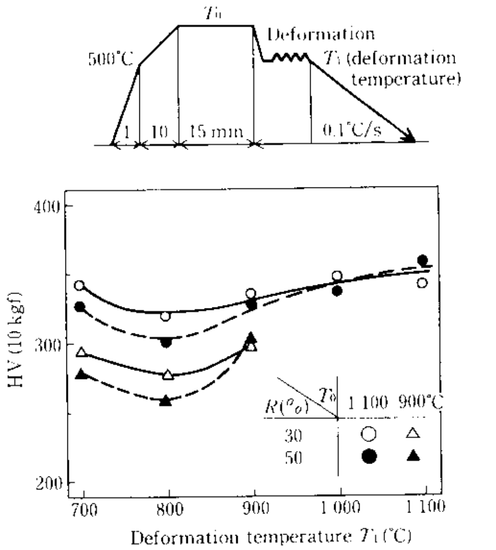

Fig. 5 Effects of deformation temperature on hardness of specimen cooled by 0.1°C/s after hot-deformation

In other words, γ grain recrystallization and cementite precipitation did not always proceed simultaneously

(3) The hardness after cooling did not depend on the reheating temperature, and the material deformed at 800°C showed the lowest hardness. Conversely, the hardness was greater in the material subjected to low-temperature deformation at 700°C. The effect of deformation rate indicated that heavy deformation at 50% had a greater effect on softening than lower rates.

The foregoing results suggest that low-temperature rolling was effective for accelerating direct softening.

4.3 Level of Softening and Mechanical Properties after Multipass Rolling

Rolling was conducted by a small rolling mill under the conditions described in Sec. 3.4, with subsequent air cooling, water cooling or insulated cooling. The microstructures thus obtained are shown in **Photo 3**, while the effects of the rolling conditions on the hardness and reduction of area are shown in **Fig. 6**.

(1) The material reheated to a low temperature and finished at a low temperature (LLR) had very low hardness and an improved reduction of area compared with the material reheated at a high temperature and rolled at a high temperature (HHR) or rolled at a low temperature (HLR). This effect was especially marked in the material air-cooled after rolling.

(2) The microstructure of both the air-cooled material and slow-cooled material consisted of pearlite and proeutectoid cementite. When air cooling, the pearlite of the material reheated to a high temperaure and rolled at a high temperature shows the finest lamellar spacing, and the proeutectoid cementite of this material developed into thick plates. In contrast to this, the mateial reheated to a low temperature and finished at a low temperature with subsequent air cooling had a fine pearlite grain size and a wide lamellar spacing. The microstructure of this air-cooled material was mostly dotted with proeutectoid cementite. As shown in the microstructure of the water-cooled material, the amount of proeutectoid cementite precipitated increased with increasing

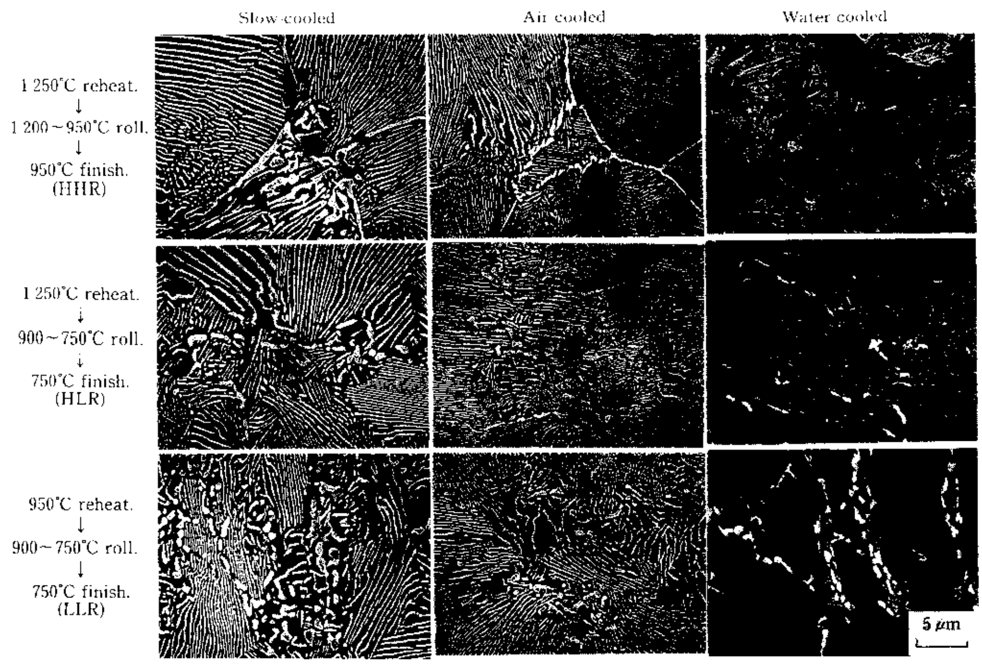

Photo 3 Observation of as-rolled microstructure by scanning electron microanalyzer

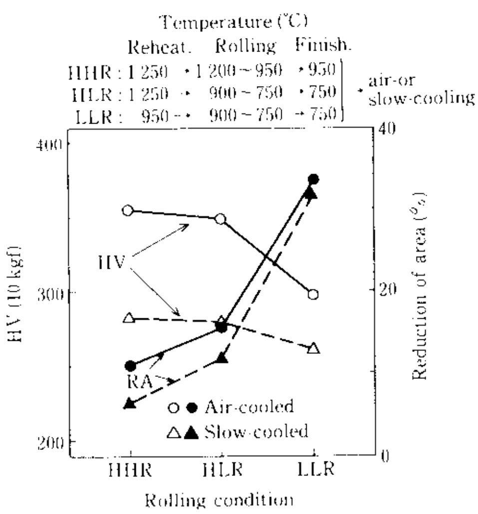

Fig. 6 Effects of rolling conditions on hardness and reduction of area

degree of TMCP; this shows that low-temperature rolling accelerated the precipitation of cementite. In particular, the microstructure of the material reheated to a low temperature and rolled at a low temperature had greatly refined grains, and exhibited a decrease in the precipitation of plate-like cementite compared with the material reheated to a high temperature and rolled at a high temperature, and the material reheated to a high temperature and rolled at a low temperature. This tendency was particularly apparent in the slow-cooled materials.

It is apparent from these results that the combination of low-temperature reheating and low-temperature rolling accelerated direct softening and prevented the plate-like precipitation of proeutectoid cementite, thus being very effective for improving the mechanical properties, and especially ductility.

5 Discussion

5.1 Contribution of Hot Rolling to γ Grain Recrystallization and Precipitation of Proeutectoid Cementite

As shown by the foregoing experimental results, to achieve direct softening of a high-carbon chromium steel for ball bearings in the as-hot-rolled condition, it is necessary to appropriately control the reheating temperature, recrystallization behavior of the γ grains, precipitated form of the proeutectoid cementite, and cooling rate. Therefore, an examination was made of the contribution of hot rolling to the behavior of γ grain recrystallization and proeutectoid cementite precipitation. The γ grain recrystallization and proeutectoid cementite precipitation were investigated for reheating at 1 100°C and 900°C and rolling at a reduction of 30%. An example of this investigation is summarized in **Fig. 7** a–d, which illustrate the following:

(1) When the reheating temperature was 1 100°C, recrystallization did not proceed while rolling at 900°C. When the reheating temperature was 900°C, however, recrystallization proceeded well, even immediately after rolling at this temperature. In other words, the finer the grain size before rolling, the more easily recrystallization occurred. Reheating

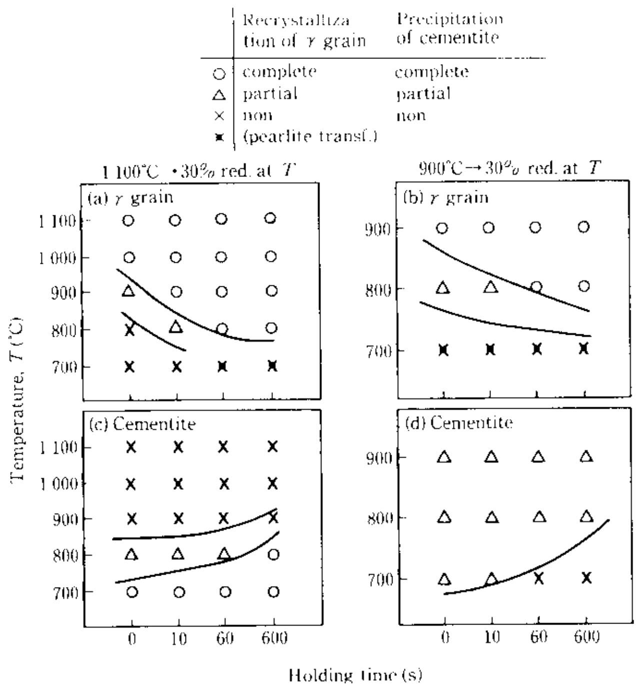

Fig. 7 Effects of deformation temperature and holding time on recrystallization of γ grain and precipitation of proeutectoid cementite

temperatures below 900°C are in the nonrecrystallization region, and the starting point for nonrecrystallization depends on the rolling temperature and the rolling reduction. However, a rolling temperature of 700°C is in the unstable austenite region, and the higher the degree of grain refinement, the more rapidly transformation would be completed.

(2) The precipitation of proeutectoid cementite occurred at below 800°C when the reheating temperature was 1 100°C. When the reheating temperature was 900°C, this precipitation was at less than 900°C. The finer the grain size, the more rapidly precipitation proceeded. As shown for the material reheated to 1 100°C and held at 800°C, the starting and ending time for γ grain recrystallization did not coincide with the starting time of proeutectoid cementite precipitation. The higher the rolling reduction, the more rapidly the recrystallization of γ grains and cementite precipitation would proceed, although this is not shown by the figures.

It is apparent from the foregoing results that the recrystallization behavior of γ grains in high-carbon chromium steels for ball bearings after hot rolling is very similar to that of niobium steels frequently used in steel plates. It is considered that the retardation of recrystallization in niobium steels has a close correlation with the precipitation of carbonitrides of niobium and the presence of solute niobium atoms.[6,13] In contrast to this, the retardation of recrystallization in high-carbon chromium steels for ball bearings may be caused by the presence of carbides of chromium that tend to form carbides, and by the effect of pinning the γ grain boundaries by the solute elements of carbon and chromium; from the similarity to the retarded recrystallization of γ grains that particularly occurs in such alloy steels for machine structural use as SCM 435 and SCr 420, it is judged that the main cause would be pinning the γ grain boundaries by the solute element of chromium.[1,14] This can also be deduced from the experiment result that the precipitation of proeutectoid cementite did not contribute to the retared recrystallization of γ grains.

It might be thought that the transformation from austenite (γ) to pearlite would proceed by a mechanism similar to that for austenite (γ) to ferrite (α) transformation of niobium steels. In other words, it is considered that, in niobium steels, the nucleation of ferrite is accelerated by rolling in the nonrecrystallization region by (1) an increase in the area of the γ grain boundaries due to flattening of the γ grains, (2) an increase in the γ grain nucleation rate at the grain boundaries, and (3) the nucleation that occurs in annealing twins, deformation bands, etc. It is considered that, as a result, the austenite to ferrite transformation is accelerated.[15] It can be understood that, in high-carbon chromium steels for ball bearings, a similar phenomenon proceeds in the form of cementite precipitation in place of α.

The existence of insoluble carbides resulting from low-temperature reheating is one of the factors to be noted in the accelerated softening for the combination of low-temperature reheating and low-temperature rolling. The minimum temperature for the complete solution of carbides in the sample steel used is about 1 000°C. When a specimen quenched after low-temperature reheating was observed, many insoluble carbide particles of less than 1 μm were found. It can be expected that the presence of these carbides would accelerate pearlite transformation due to the suppression of γ-grain coarsening during reheating[16] and the effect of a decrease in γ stability.

Therefore, it is possible to control the dispersion of proeutectoid cementite by starting from the stage at which γ grains are fine before working by adopting low-temperature reheating and by utilizing low-temperature rolling in the nonrecrystallization-temperature region. In other words, by causing proeutectoid cementite to precipitate at the elongated γ grain boundaries and recrystallization and grain refinement to proceed after that, it is possible to impart the necessary mechanical properties to a steel by accelerating the transformation and ensuring uniform dispersion of the proeutectoid cementite.

5.2 Effect of the Precipitated Form of Proeutectoid Cementite on Workability

It was earlier described that direct softening can be accomplished by conducting slow cooling after high-temperature reheating and high-temperature rolling. It is to be expected, however, that the plate-like precipitation of proeutectoid cementite would be enough to adversely affect workability. The degree of this adverse effect was about 10%—a very low level in the material reheated to a high temperature and rolled at a high temperature (HHR), as shown by the resulting reduction of area in the tensile test in Fig. 5. In contrast, this degree of adverse effect increased in the material rolled at a low temperature (HLR), and further increased to about 30% in the material reheated to a low temperature and rolled at a low temperature (LLR). Therefore, although direct softening could be achieved simply by slow cooling after normal hot rolling, it is highly probable that this method would impair the quality after the secondary cold-working process. Thus, this method is undesirable in practice.

In contrast, low-temperature rolling that can change the precipitated form of proeutectoid cementite from plates to dots may eliminate the foregoing drawback. It seems that the effect of finely dispersed cementite, as well as the refinement of microstructure, contributes greatly to this improvement. Therefore, when an improvement in cold-workability is strongly desired, low-temperature rolling is necessary and will be effective.

5.3 Shortening the Spheroidizing Annealing Time by TMCP

As already stated, the combination of low-temperature reheating and low-temperature rolling accelerated direct softening, and improved the microstructure and such mechanical properties as cold-workability. However, it is necessary to examine whether there is a any problem concerning the shape of spheroidized carbides[16] that has a great effect on rolling contact fatigue—one of the vital qualities of high-carbon chromium steel ball bearings. Therefore, the effect of the spheroidizing annealing treatment that governs the shape of spheroidized carbides was investigated.

The effect of spheroidizing annealing was evaluated for the steels experimentally rolled under the conditions shown in Sec. 3.4 and given different annealing treatment times.

Condition SA1: 780°C × 9 h → cooling to 600°C at 10°C/h → air cooling to below 600°C ...... Required time, 27 h

Condition SA2: 780°C × 9 h → cooling to 600°C at 30°C/h → air cooling to below 600°C ...... Required time, 15 h

The microstructures obtained after this treatment are shown in **Photo 4**, and the hardness and reduction of area in the tensile test are shown in **Fig. 8**. The following deductions can be made:

(1) Compared with the material reheated to a high temperature and rolled at a high temperature (HHR) or rolled at a low temperature (HLR), the material reheated to a low temperature and rolled at a low temperature (LLR) had a lower hardness and softened well under the same conditions. This effect was especially marked in the slow-cooled materials.

(2) In both cases of air cooling and slow cooling, the material reheated to a high temperature and rolled at a high temperature (HHR) frequently exhibited

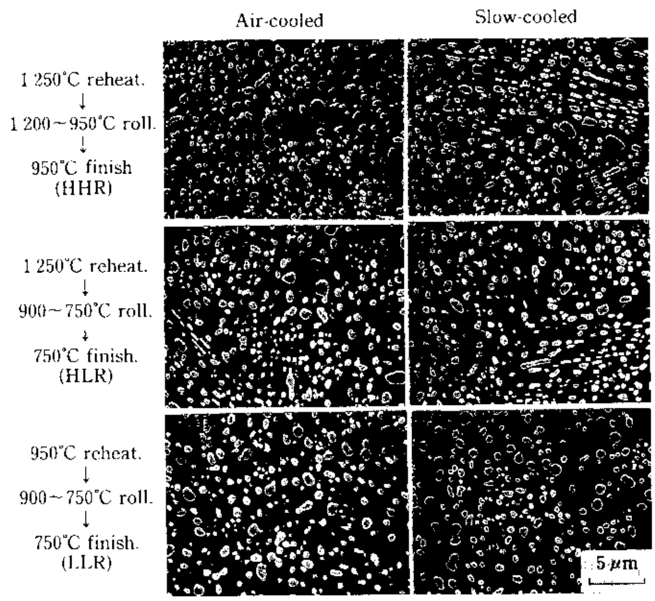

Photo 4 Observation of spheroidized microstructures of steels produced in various rolling conditions

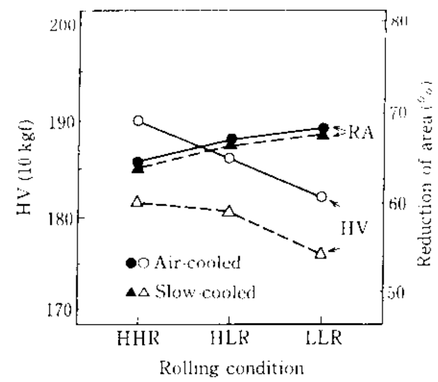

Fig. 8 Effects of rolling conditions (see Fig. 5) on hardness and reduction of area after spheroidized annealing (780°C, 9 h → 30°C/h → 600°C)

nonuniformity in the size and shape of carbides. In contrast, the material reheated to a low temperature and rolled at a low temperature (LLR) had a spherical carbide shape of uniform size in many cases. Any difference due to heat treatment time hardly occurred.

(3) In both cases of air cooling and slow cooling, the material reheated to a low temperature and rolled at a low temperature (LLR) had the lowest hardness. When a comparison is made between the air cooled materials, the hardness level of the LLR material obtained under spheroidizing annealing conditions SA2 was lower than that of the HHR and HLR materials obtained under spheroidizing annealing conditions SA2. The LLR material had the highest value for reduction of area.

It is apparent from the foregoing that the material reheated to a low temperature, rolled at a low temperature and then air-cooled was superior to the ordinarily rolled material in respect of the shape of carbides after spheroidizing annealing and the mechanical properties, and that the spheroidizing annealing time was shorter. Hoshino et al.[17] have reported for 0.52% C steel that low-temperature rolling accelerated the spheroidizing of cementite in medium- and/or high-carbon steels. Chattopadhyay et al. also reported for 0.74% C steel that the finer the pearlite grains, the more spheroidizing would proceed.[18] However, the reasons for this were not always clarified.

The probable reasons are as follows. When spheroidizing annealing is conducted according to the slow-cooling method, reheating to a temperature just above the Ac_1 point and holding at this temperature would cause part of the lamellar pearlite and proeutectoid cementite to remain as insoluble carbides. With the slow-cooling process after holding, precipitation and growth would occur with these carbides as nucleation sites to form spheroidized cementite. Softening by this treatment is considered to be because solid solution hardening atoms such as carbon, manganese and chromium are partly precipitated in the form of carbides, and therefore solid solution hardening is reduced.[19-23] Therefore, the more uniform the shape, size and distribution of the insoluble carbides, the more uniform the structure after spheroidizing annealing. it is desirable that the microstructure before heat treatment be also homogeneous.

Furthermore, the existence of many grain boundaries that are main paths for diffusion is advantageous, because the spheroidizing rate depends on the precipitation and coarsening of carbides at the nucleation sites and α interfaces, as well as on the diffusion rate of carbon atoms to the nucleation sites. Also, in the case of reheating and holding at a temperature just above the Ac_1 point, the finer the microstructure, the larger the γ/α interface area and the shorter the diffusion distance. It is reasonable to postulate that, for these reasons, the finer the microstructure, the more rapidly the spheroidizing of carbides would proceed. In the material reheated to a low temperature and rolled at a low temperature, fine pearlite grains and granular proeutectoid cementite were uniformly distributed to meet the foregoing conditions. In addition, a fine microstructure is advantageous in terms of the conferred improvement in ductility.

As is apparent from the foregoing analysis, the combination of low-temperature reheating and low-temperature rolling is favorable for improving the mechanical properties, both in the as-hot-rolled condition and after the spheroidizing annealing treatment.

6 Results of Trial Manufacture by Commercial Production Equipment

Rolling on a production rolling mill was conducted according to the results from the laboratory experiments. **Figure 9** shows an example of the hardness distribution in the rolling direction of round bars 130 mm in diameter and made of the SUJ2 high-carbon chromium steel for ball bearings. With the bar subjected to

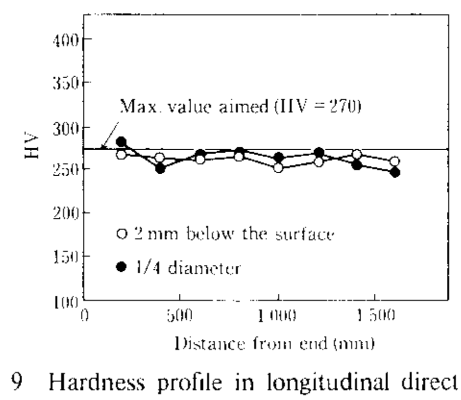

Fig. 9 Hardness profile in longitudinal direction of 130 mmϕ bar produced by TMCP

TMCP, the section hardness was not more than HV 270 a Vickers hardness level necessary for sawing. This level is close to that of steels subjected to the softening annealing treatment. A sawing test of the round bars was then conducted. It took 280 s to saw the bar rolled according to the conventional rolling method, while it took 105 s to saw the bar produced by using TMCP. The cutting speed was about three times as high as that of round bars rolled by the conventional rolling method, and the working efficienty was equal to that of materials subjected to softening annealing.[9,10]

7 Conclusions

To omit softening annealing in the manufacture of thick round bars of high-carbon chromium steels for ball bearings by applying the thermomechanical control process (TMCP), investigations were made into the recrystallization behavior of γ grains and the precipitation behavior of proeutectoid cementite, as well as the relationship between various treatment conditions and mechanical properties after slow cooling, using SUJ2 high-carbon chromium steel for ball bearings. The results are summalized as follows:

(1) The combination of low-temperature reheating and low-temperature rolling was effective for accelerating softening and ensuring uniform distribution of proeutectoid cementite. it was also very effective for shortening the spheroidizing treatment time by refining the pearlite structure and proeutectoid cementite.

(2) Low-temperature rolling accelerated the precipitation of proeutectoid cementite. In this case, the precipitated cementite was granular, and did not have the shape of the plates observed after high-temperature rolling.

(3) Direct softening by the combination of high-temperature reheating, high-temperature finishing and final slow cooling caused plate-like precipitation of proeutectoid cementite and lowered the ductility during secondary working. This decreased ductility could be prevented by applying low-temperature rolling.

(4) Round bars were manufactured in an experiment on a commercial production rolling mill according to the knowledge obtained from this study. These bars were cut at a sawing speed about three times that of bars produced by normal rolling, and the working efficiency was equal to that of materials subjected to softening annealing.

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