Production of High-carbon Chromium Bearing Steel in Vertical Type Continuous Caster*

By Toshikazu UESUGI**

Synopsis

The rolling contact fatigue life of bearing steel is improved with decreases in the oxide nonmetallic inclusions. The oxygen content of high carbon chromium bearing steel has been reduced to an average level of 5.8 ppm. This is accomplished through the combined processes of an electric arc furnace, a ladle furnace, an R-H vacuum degassing vessel and a continuous caster.

The rolling contact fatigue life of high-carbon chromium bearing steel thus manufactured has accordingly doubled to tripled on the test of a thrust type machine if compared with the results of the conventional vacuum degassed, ingot cast steel.

The supply of extremely low oxygen steel to the caster has resulted in the elimination of such troubles as nozzle clogging. From the operational standpoint, it has been the main contributor to a record 10 000 t of continuous cast high-carbon chromium bearing steel from one tundish-one nozzle without interruptions.

It has been demonstrated in the life tests that neither sulfur nor titanium has an influence on the life when the levels of these elements are held down to a minimum in the high-carbon chromium bearing steel. The life is further extended by the cold working inherent to cold pilgered tubes. The improvement has been found out in the tests to double to triple life of hot worked hollow tubes.

I. Introduction

Improvement in the rolling contact fatigue life of rolling bearings (the number of total stress cycles or the time to the fracture of bearings or to the occurrence of flakings) is of great importance in designing the bearings of greater reliability, smaller size, lighter weight and higher performance. It is well known that the life can be remarkably improved by a reduction of oxide inclusions, so the vacuum degassing treatment is specified in JIS for high-carbon chromium bearing steel.

It is necessary, in order to produce low oxygen molten steel, to separate the melting process with the oxidation reactions from the refining process involving the reduction reactions. The separation is also favorable for the productivity. Due considerations must be also given to the selection for the refractory material of the reactive vessel. The casting method should be the continuous casting to achieve a minimum of oxygen, especially the vertical type continuous caster is the most desirable with regard to uniformity in the distribution of nonmetallic inclusions.

SUJ2 (SAE52100) high-carbon chromium bearing steel has been produced at Sanyo Special Steel through the combined processes of an electric arc furnace (EF)–a ladle furnace (LF)–an R-H vacuum degassing vessel (RH)–a vertical type continuous caster (CC) introduced to put the above principles into practice.

The manufacture and quality of SUJ2 (SAE52100) will then be discussed below.

II. Manufacturing Facilities and Operations

1. EF–LF–RH

1. Facilities

The facilities of EF, LF and RH are outlined in Table 1. Some features of the equipments are;

(1) EF: Water cooled panels are embedded in 75 % of the sidewalls and 70 % of the roof to enable the furnace to operate at a maximum secondary voltage of 900 V.

(2) LF: Carbon-magnesia bricks are used on the slag line and high-alumina bricks in the other areas, to reduce the oxygen content in the melt due to little unstable oxides such as SiO₂ in the refractories.

The double-porous plug method is moreover applied to stir the molten steel in the ladle. The chemical composition of the ladle bricks is indicated in Table 2.

2. Operations

(1) EF: The schematic power program is shown in Fig. 1. Since steel is reduction-refined in the ensuing LF process, the steel is tapped in the barely

<table>
<thead>
<tr>
<th>Facility</th>
<th>Shell diameter</th>
<th>Transformer capacity</th>
<th>Max. secondary current</th>
<th>Max. secondary volt</th>
<th>Rated secondary volt</th>
<th>Electrode diameter</th>
<th>Av. tap to tap time</th>
<th>Charge weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF</td>
<td>7.0 m</td>
<td>70 MVA</td>
<td>70 kA</td>
<td>900 V</td>
<td>585 V</td>
<td>24 inches (610 mm)</td>
<td>75 min</td>
<td>150 t</td>
</tr>
<tr>
<td>LF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RH</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 1. Major particulars of EF, LF and RH.

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deoxidized state. The oxidizing slag in the ladle is completely raked off from the tapped steel by a slag dragger.

(2) LF: The chemical compositions of the ladle furnace bricks and the refining slag are considered as one of the most important factors which determine the equilibrium value in the deoxidizing reaction. Steel is treated with the high basicity slag in the aforementioned carbon-magnesia and high alumina bricks of low SiO₂. The oxygen content of SUJ2 (SAE52100) thus produced through the EF–LF–RH–CC processes has resulted in 5.8 ppm on the average, as will be discussed later, being 2.5 ppm lower than in the conventional method of the EF–RH-ingot. An example of the chemical composition of the slag for SUJ2 (SAE52100) at the end of the treatment is shown in Table 3. While such high basicity slag and strong stirring power of the LF can facilitate desulfurization, the sulfur content is controlled in the actual operation to 7 to 15×10⁻³ % for the sake of the machinability. Figure 2 demonstrates an example of the change in the sulfur content of the LF process.

The operational conditions of LF are briefly described below.

Volume of steel : 140 t
Treating time : 30 to 50 min
Stirring method : Nitrogen stirring by double porous method
Basicity of slag : CaO/SiO₂=4.0 to 5.0
Treating temperature : 1 520 to 1 570 °C

The steel is deoxidized with aluminum after the
ships among the air volume coming into a tundish, the volume of the introduced inert gas and the oxygen concentration in the tundish, which can be expressed by

\[ C = \frac{0.20}{Q+X} \exp \left( -\frac{Q+X}{V} \cdot \frac{273+T}{273} \cdot t \right) \\
+ 0.2 \cdot \frac{X}{Q+X} \]

where, 
- \( C \): oxygen concentration in tundish (wt%) 
- \( t \): elapsed time from the introduction of inert gas (min) 
- \( V \): volume of tundish (8 m³) 
- \( T \): temperature in tundish (1 000 °C) 
- \( Q \): volume of inert gas introduced (Nm³/min) 
- \( X \): volume of air intruded (Nm³/min).

Equation (1) was derived from the volume balance among the volume of air intruding into a tundish, the volume of inert gas introduced \((Q)\) and the volume of gas emitted from the tundish \((Q+X)\) on the assumption that the initial concentration of oxygen was 0.2.

According to Fig. 4, the volume of the intruding air should be therefore almost nil and the complete seal between the tundish and the cover is a requisite so as to maintain the oxygen content at less than 0.1% in the tundish and also to reduce the consumption of inert gas \( (N_2 \text{ or } Ar) \) to as little as possible.

Figure 5 is an example showing a variation of the oxygen content in the actual operation of this developed tundish right before the start of the teeming molten steel. These values are in agreement with the calculated ones for absence of the intruded air: \( X=0 \), and it is seen that the oxygen content is kept within 0.1% for an entire period of the casting.

2. Operations

The casting conditions for SUJ2 (SAE52100) are

<table>
<thead>
<tr>
<th>Table 5. Casting practice of SUJ2 (SAE52100).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Withdrawal speed</td>
</tr>
<tr>
<td>Specific cooling water ratio</td>
</tr>
<tr>
<td>Change of level in mould</td>
</tr>
</tbody>
</table>

listed in Table 5. The mean oxygen content has been reduced to 5.8 ppm and also the oxide inclusions are substantially decreased, as will be discussed later, by means of the extreme low oxygen refining operation in steelmaking and the casting under completely oxygen-free atmosphere in the continuous caster. Further, in the operations it has become feasible, due to little buildup of the inclusions on the inner surfaces of the immersion nozzles, that the number of heats cast from one tundish—one nozzle is 68, namely 10 150 t of blooms. Table 6 reveals the conditions for the record number of heats continuously cast without interruptions.
3. Rolling and Subsequent Processes

SUJ2 (SAE52100) blooms produced through the EF-LF-RH-CC processes as stated above are processed to billets in the 3-roll planetary mill (PSW) after the reheating and the soaking, which are subsequently rolled to bars in the rolling mill. For tubes, they are manufactured by rolling or by extrusion from the PSW billets and frequently followed by cold working in the cold pilger mills. In addition, appropriate heat treatments are given between the processes.

III. Quality Level of Continuous Cast SUJ2 (SAE52100)

1. Specimen Preparation and Experimental Procedures

1. Chemical Composition of Specimens

The chemical composition of the material used for the fatigue life tests is given in Table 7. The thrust type test specimens machined were heated at 835 °C for 20 min, oil-quenched, tempered at 180 °C for 90 min and subsequently air-cooled. By these treatments, the hardness of the specimens becomes HRC 62 to 63.

2. Analysis of Oxygen

Oxygen contents were measured with the quantitative oxygen analyser by an inert gas fusion conductivity method calibrated at two points by NBS 1094 and an in-house standard sample. The oxygen content lower than 4.5 ppm, the value of NBS 1094, was determined by the extrapolation.

3. Evaluation of Cleanliness

JIS method or ASTM E45 method D was at first considered for the evaluation of the improved cleanliness obtained by a reduction in the oxygen content. No quantitative differences in the values, however, were distinctly revealed in these methods, then the “SAM” method suitable for the inclusion ratings of bearing steel described in ASTM A295-84 was employed. In this method, type A sulfides which are not considered significant in fatigue life, type C silicates which occur infrequently in the subject steel and type D thin globular oxides are disregarded as the rating objects. The cleanliness is evaluated as follows:

   (1) B Type Inclusion
      (a) All B thin fields with a rating of 1.5 or higher are recorded for all samples.
      (b) All B heavy fields with a rating of 1.0 or higher are recorded for all samples.
      (c) The above numbers are summed and normalized by dividing by the total rated area of all samples in square inches.

   (2) D Type Inclusions
      (a) All D heavy fields with a rating of 0.5 or higher are recorded for all samples.
      (b) Fields of 0.5 are counted as one unit; fields of 1.0 as two units; fields of 1.5 as three units and so on.
      (c) The number of units is summed and normalized by dividing by the total rated area of all samples in square inches.

   This method is considered more sensitive to the metallographically observable difference in cleanliness than the conventional method A or D.

4. Fatigue Life Test

The thrust type rolling contact fatigue testers were used for the life tests. It has been recognized that the life obtained with these testers is qualitatively in good agreement with that of the actual bearings. The test conditions are as follows;

- Maximum hertzian stress ($P_{max}$): 500 kgf/mm²
- Stress repetition rate: 1 800 c.p.m.
- Lubricant: No. 60 spindle oil

5. Fatigue Life Test Specimens Including Axis

The fatigue life test specimens including an axis of the rolled bars were taken as illustrated in Fig. 6.

6. Indication of Flaking Site

The flaking sites on the running track expressed as an angle from an axis of the bars are plotted in Fig. 10 where the results in all the quadrants were summarized in the quadrant I.

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Table 6. Conditions for 10 000 t continuous cast. (with one tundish-one nozzle)

<table>
<thead>
<tr>
<th>Date</th>
<th>June 23 to 27, 1985</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>94.45 h</td>
</tr>
<tr>
<td>Number of heats cast</td>
<td>68</td>
</tr>
<tr>
<td>Tonnage of blooms</td>
<td>10 150 (t)</td>
</tr>
<tr>
<td>Yield of blooms (Blooms/melt)</td>
<td>99.6 (%)</td>
</tr>
</tbody>
</table>

Table 7. Chemical composition of SUJ2 (SAE52100) tested. (wt%)
7. Fatigue Life Test for Cold Worked Tubes

The cold worked tubes and their hollow tubes heated at 650 °C were flattened to plates and the fatigue life tests were conducted on the outer surfaces of the tubes.

2. Quality Level

1. Oxygen Content

The histograms of the oxygen contents are presented in Fig. 7 for the SUJ2 (SAE52100) produced by the continuous casting (CC) and the conventional ingot casting (IC) processes. The CC steel is lower in the oxygen content by 2.5 ppm on the average and also in the maximum values as compared with the IC steel.

As NBS 1094, the lowest oxygen standard sample, contains 4.5 ppm oxygen, it may be said that the reliability of the analyses smaller than 4.5 ppm is doubtful. However, it is to be reminded that the SUJ2 (SAE52100) of lower than 5 ppm oxygen has been produced. This level of the oxygen content is almost equivalent to that of vacuum arc remelted steel.

2. Cleanliness

The distinct difference in the oxygen content between the CC and IC steels prompted us to investigate their cleanliness. Table 8 shows the rated results of the cleanliness by the “SAM” method. According to the results, it is understood that B thin type inclusions with a rating of 1.5 or higher, B heavy type with 1.0 or higher, and D heavy type with 0.5 or higher scarcely exist in the CC steel. It is, as stated earlier, the lower oxygen content that has improved the rating of the CC steel.

3. Fatigue Life

(1) Fatigue Life of CC Steel

The CC steel has such low oxygen content that the longer life can be expected. The life test results on the CC steel currently produced are shown in Fig. 8. These results, falling in an area extrapolated from the curves previously obtained for the relationship between the oxygen content and the L10 life (the probability of 90 % survival), have doubled to tripled as compared with those corresponding to the 8 to 9 ppm average oxygen content in the IC steel.

(2) Center Segregation and Fatigue Life

The center segregation in the CC steel has been said to be severer than that in the IC steel and its influence on the various properties deserves some attention.

Since it was feared that the rolling contact fatigue life for SUJ2(SAE52100) would be shortened with carbides or nonmetallic inclusions concentrated in the center of steel bars, the fatigue tests were performed on the specimens where the center showed on the running surface as shown in Fig. 6. The microstructure in the center of the steel is shown in Photo.
The results of the fatigue tests are demonstrated in Fig. 9. The relationship between the life and the flaking site (an angle of the flaking site measured from the axis of a steel bar) is plotted in Fig. 10. The absolute values of the life are better with the CC steel of the lower oxygen content than those with the IC steel, while little difference is found in the flaking sites between them. Furthermore, there is no tendency for the occurrence rate of the flaking to concentrate in the center portion of the CC steel.

The oxide inclusions, which trap carbon diffused by the rolling stress, work as a medium to form the micro-cracks or the platelike carbides. Whereas the degree of the carbon segregation, C/Co (where C: carbon at the center, Co: ladle analysis carbon) is approx. 1.15 in the CC steel, it is 0.9 to 1.15 in the IC steel depending on the location of the ingot. This tells that the carbon segregation is not so high in the CC steel as is generally expected.

Although the higher carbon concentration in the matrix causes the lower life, the life is not influenced even by an increase in the diffused carbon in the absence of the oxide inclusions which seize it. It is, therefore, reasoned that the oxide inclusions evenly dispersed throughout the entire section in the CC steel prevent the concentration of the flaking sites in the center of the CC steel.

Currently a reduction of oxygen, sulfur, titanium and so on has been attempted everywhere in order to improve the fatigue life. The specimens of extreme low impurities were manufactured through the EF–LF–RH–CC processes for the fatigue life tests. The results obtained are again shown in Fig. 8, where the previous relationship between the oxygen content and the L10 life is seen. It can be said according to this figure that even though the impurities other than oxygen are held to a minimum, the life may not be always extended and its plots fit in a band governed by the relationship between the oxygen content and the L10 life. The observation that the IC steel depending on the location of the ingot.
life is not improved by a reduction of sulfur and
titanium has been confirmed by another experiment,\(^9\)
the results of which are qualitatively consistent with
those of the present work.

(4) Cold Working and Fatigue Life
It has been found that the cold pilgering process
with an approx. 70 % reduction in area extends
the fatigue life of SUJ2(SAE52100) more than three
times on the average due to the breaking of the oxide
inclusions and the elongation of the sulfides.\(^6\) This
phenomenon has been observed on the specimens
containing more than 6 ppm of oxygen.

While it was assumed that the more oxide inclusions
were present, the more clear effect on the improve-
ment of the life would be identifiable owing to the
more breakups of them, the influence of the cold
pilgering on the fatigue life was investigated in this
work with the lower content of oxygen, using the
same materials as in Sec. III.2.3.(3).

The results are included in Fig. 8. It is seen that
the life has been improved, as in the case of the higher
oxygen content, by the cold working and extended
approximately from two to three times with some
variation in the degree of the improvement. This
improvement may be attributable to the breaking of
the oxide inclusions and the elongation of the sulfides
as previously reported. It is, further, conceived that
the effect of the breaking would be rather greater than
the elongation because of the low sulfur contents in
the specimens.

The tube manufactured by the CG-cold pilgering
process for mass-produced SUJ2(SAE52100) is ac-
cordingly considered to have the longest life.

4. Summary
The excellent fatigue life is evidenced in SUJ2
(SAE52100) produced by the CC process due to
the reduced oxide inclusions. The causes for such
improvement of the life by the reduction of the oxide
inclusions are reasoned as follows: Carbon diffused
by the rolling contact stress is trapped by the dis-
locations in an area of stress concentration between
oxide inclusions in the vicinity of the area influenced
by the maximum shear stress under the running track.
It subsequently causes either the micro-cracks or
forms the platelike carbides when more carbon is
diffused, which result in micro-cracks. The micro-
cracks are less likely to occur in the CC steel where
the oxide inclusions are minimal. It would be due
to the fewer oxides throughout the section that the
life in the CG steel is improved without the concen-
tration of the flaking sites in the center area in spite
of somewhat more carbon segregation there.

IV. Conclusions
The manufacturing process, EF–LF–RH–CC, and
the quality levels of SUJ2(SAE52100) have been
discussed.

The conclusions obtained are as follows:
(1) The oxygen content in the CC steel has dropped by 2.5 ppm below that in the conventional
IC steel.
(2) A reduction of the oxygen content in the
molten steel has resulted in the elimination of troubles
such as the clogging of the immersion nozzle caused
by the alumina precipitation and contributed to a
record 10 000 t of continuous cast steel through one
tundish–one nozzle without interruptions.
(3) The fatigue life of the CC steel has doubled
to tripled if compared with the life of the conventional
IC steel.
(4) The fatigue life is further extended two to
three times by cold working if the oxygen content is
as low as 5 ppm.
(5) A reduction of sulfur and titanium does not
contribute to the improvement of the fatigue life, and
the life still fits in the relationship between the oxygen
content and the \(L_{10}\) life. These results would indicate
that the major influence on the life is exerted unilater-
ally by the oxygen content even though it is kept so
low.

REFERENCES
1) M. Ueno, H. Nakajima and S. Ikeda: Tetsu-to-Hagane, 46
(1960), 344.
2) K. Furumura and K. Hirakawa: NSK Bearing J., (1979),
No. 638, 1.
3) K. Kobayashi, K. Tsubota and T. Sakajo: Tetsu-to-Hagane,
70 (1984), S1228; Trans. ISIJ, 23 (1985), B20.
6) T. Onishi, S. Kawasaki, Y. Suzuki, K. Shiwaku, N. Ueno
7) Y. Takata, E. Kikuchi, K. Kuma, K. Mori and R.
Komatsu: Tetsu-to-Hagane, 70 (1984), S1366.
8) K. Tsubota, K. Onishi, T. Sakajo and A. Ishihara: Tetsu-
to-Hagane, 70 (1984), 854.
9) K. Kobayashi, K. Tsubota and T. Sakajo: Tetsu-to-Hagane,
71 (1985), S1556; Trans. ISIJ, 26 (1986), B82.