Dimension Control in the Machining of Bearing Steel in Supercooled Austenite*

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Synopsis

On machining of bearing steel in supercooled austenite, the dimensions of a workpiece change due to thermal contraction and martensitic transformation in the cooling process after cutting. In order to obtain the precise dimensions of the workpiece at room temperature, it is necessary to predict the dimension changes and to adjust the tool paths to compensate for them in the machining process of the steel in supercooled austenite. A method to predict the dimension changes was established. A dimension control system for an NC machine tool was designed and its performance was examined.

The obtained results are summarized as follows:

(1) The thermal contraction rate of supercooled austenite of bearing steel SUJ3 is 2.2 x 10^{-5}/°C.

(2) The final dimension (L) of a workpiece is expressed by the following equation in terms of the temperature (T °C) of the workpiece during cutting and the machined dimension (l) of supercooled austenite.

\[ L = l (1.0077 - 2.2 \times 10^{-5} \times T) \]

(3) In the case when the tool wear rate is small, the final dimension is controlled precisely by means of the developed dimension control system which makes the compensation of the machining dimension for the dimension changes predicted at each temperature of workpieces on the basis of the thermal contraction rate of supercooled austenite.

I. Introduction

The manufacturing process for bearing parts such as race from high carbon-\text{Cr}-\text{Mn} bearing steel is generally as follows: steel blank → hot forging and rolling → annealing → turning → quenching and tempering → grinding. This process requires many stages of heatings and coolings and results in the loss of thermal energies and time. Despite the loss of energies, the above process has been necessary to improve the machinability of high carbon steel. Moreover, as the amount of steel to be ground becomes large because of the distortion due to heat treatment, an alternative method of grinding has been sought.

On the other hand, the authors have already developed and introduced a new method called auscutting.1~ As shown in Fig. 1, it is a composite technique consisting of machining and heat treatment in which the workpiece is quenched to just above the Mf point and is machined in this state of the steel (supercooled austenite) and subsequently is cooled to room temperature in order to complete martensitic transformation. This method might permit not only the omission of annealing but also the decrease in the amount to be ground by cutting under optimum cutting conditions. The authors have suggested the theoretical possibility of this method earlier. This paper reports the experimental results for the establishment of the dimension control system in which the thermal contraction of the material and the expansion due to the transformation are considered.

II. Method of Auscutting and Measurement of Dimension Change by Thermal Contraction and Expansion due to Transformation

I. Workpiece and Experimental Procedure

The bearing steel Class 3 (SUJ3 in JIS) was used for the material of the workpiece. The chemical compositions of SUJ3 are shown in Table 1. The workpiece was the inner race of the radial ball bearing 6320,*** 138 mm in outside diameter, 95 mm in inside diameter and 50 mm in width. It was made by the hot forging and rolling, and the spheroidization annealing was carried out according to the conventional method.**** Its hardness was HB190.

The workpiece was heated at a quenching tem-

Fig. 1. TTT diagram of SUJ3 and auscutting.

Table 1. Chemical compositions of SUJ3 (wt%).

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.95~</td>
<td>0.40~</td>
<td>0.90~</td>
<td>&lt;0.025</td>
<td>&lt;0.025</td>
<td>0.90~</td>
<td>1.20~</td>
</tr>
<tr>
<td>1.10</td>
<td>0.70</td>
<td>1.15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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*** 6320 is a designation of a ball bearing, which has the following dimensions: (inside diameter: 100 mm, outside diameter: 215 mm, width: 47 mm).
**** The quenching should be conducted continuously, subsequent to the spheroidization treatment, in order to save thermal energies. It was separated from the spheroidization annealing because the main purpose in this study was to control the machining dimensions in auscutting.
perature in a range of 825~900 °C for about 50 min in an electric furnace, quenched in an oil bath at 200 °C and isothermally retained for about 3.5 min to assume a supercooled austenite state. The temperature at which the workpiece was withdrawn was about 220 °C, just above the $M_s$ point. Immediately afterwards, it was chucked on a lathe and was turned (auscut). The cutting condition remains the same throughout this study and is described in Section III. 2.2 in detail.

In order to keep the temperature of the workpiece constant during auscutting, an insulated chuck with a ceramic heater shown in Fig. 2 was used. After auscutting, the workpiece was mounted on the device shown in Photo. 1 and the temperature and the dimension change on the outside surface were measured in the course of cooling in air. In order to prevent the workpiece from being cooled partially, a heat-resistant board made of an epoxy resin was used as a support for the workpiece. The temperature of the workpiece was measured with a surface thermometer. The dimension change was measured on photographs taken by using eight dialgauges.

2. Experimental Results

Figure 3 shows the relationship between the dimension change and the temperature of the workpiece after auscutting when the quenching temperature is 850 °C. The temperature of the workpiece just after auscutting is about 220 °C and does not fall during auscutting, though it takes about 3 min from withdrawing the workpiece from the oil to finishing auscutting. This result indicates the effect of controlling the temperature of the pawl in the insulated chuck at about 220 °C and it suggests that the heat input by cutting is approximately equal to the heat loss in air in the case where there is no heat transfer between the workpiece and the chuck. The outside diameter just after auscutting is 135.5 mm, and the workpiece contracts up to about 170 °C at a constant rate and after that expands as it is cooled in air. When the quenching temperature is 850 °C, 170 °C corresponds to the $M_s$ point. The volume expansion due to martensitic transformation takes place during cooling from 170 °C to room temperature and, consequently, the size of the workpiece increases. The dimension measured at regular intervals of 45 deg on the circumference of the workpiece is shown in Fig. 3. In contrast to the round shape just after auscutting, the quench distortion (maximum diameter−minimum diameter) of about 0.04 mm after quench hardening is observed.

Figure 4 shows the dimension change in outside diameter after auscutting at various quenching temperatures from 825 to 900 °C. In all cases, the temperature of the workpiece before auscutting is 220 °C and the machining dimension is 135.5 mm. Each curve indicates the mean dimension measured at intervals of 45 deg. Each workpiece contracts up to the $M_s$ point at a constant rate even when the quenching temperature is varied, and the thermal contraction rate ($dL/°C$) of supercooled austenite is $2.2 \times 10^{-5}/°C$ according to Fig. 4. When the quenching temperature is 825 °C, 850 °C, 875 °C and 900 °C, the $M_s$ point is 200 °C, 170 °C, 145 °C and 120 °C, respectively. When the quenching temperature is raised, the $M_s$ point drops. There is an appreciable difference in the final dimensions of workpieces. The
final dimension is maximum (+0.39 mm) at the quenching temperature of 850 °C and is minimum (+0.25 mm) at that of 900 °C. As the difference is very small (0.03 mm) in the case of 825 °C, 850 °C and 875 °C, it is considered that the final dimension is almost constant at the range of a quenching temperature (800°-850 °C) in practical use even when the quenching temperature is varied. The final dimension is about 0.39 mm larger than the machining dimension, when the temperature of the workpiece before auscutting is 220 °C. If the temperature of the workpiece before auscutting changes, the final dimension changes on the basis of the thermal contraction rate of supercooled austenite (2.2 x 10^-5) as shown in Eq. (1) using the machining dimension (l) and the temperature of a workpiece before auscutting (T). It can be constant by controlling the cutting conditions and the temperature of a workpiece before auscutting.

\[ L = l + t \left( 0.39 \times 135.5 - (T - 220) \times 2.2 \times 10^{-5} \right) \]

where, \( T \) is higher than \( M_s \) point.

The bearing steel is usually tempered at a temperature from 150 to 180 °C after quenching. The dimension change (contraction) with the structural changes will occur through the tempering. The dimension change by tempering is much smaller than that by quenching; for example, the contraction rate \( \Delta l/l \) is 3.0 x 10^-4 in the case of 180 °C x 2 hr tempering. If it is necessary to strictly control the amount to be ground, the finished dimension including the contraction by tempering should be set up as the final dimension.

### III. Experiments for Dimension Control

#### 1. Dimension Control Process

It may be considered that the temperature of workpieces before auscutting changes in the range of 20~30 °C in the production process because of the change of quenching conditions and the cooling in the transfer process from heat treatment equipment. Accordingly, the method of controlling the machining dimension was designed in order to be able to obtain the desired finished dimension of a workpiece even when the temperature of a workpiece changed before auscutting. It is a method of adjusting the tool paths to compensate for the difference between the measured temperature of a workpiece before cutting and the reference temperature (most suitable temperature for auscutting).

The scheme of the dimension control system is shown in Fig. 5. It consists of an infrared thermometer to measure the surface temperature of a workpiece and a central processing unit (CPU) which calculates the amount of the dimension change by comparing the measured temperature with the reference temperature. It then transfers the result to the control unit for the tool positioning on an NC lathe. The reference temperature and the correction factor were input to the CPU. The correction factor was calculated by multiplying the required machining dimensions of each part of a workpiece by the thermal contraction rate of supercooled austenite (2.2 x 10^-5) which was obtained in the preceding experiment.

This dimension control system was used only for compensating for the change in the temperature of a workpiece which occurred due to the high temperature of a workpiece characteristic in auscutting. The change in the machining dimension due to the tool wear was not corrected. The possible method should be examined separately. In this paper, the influence of the tool wear on the finished dimension of a workpiece was investigated by measuring the temperature rise of the workpiece during auscutting.

#### 2. Experimental Procedure

##### I. Workpiece and Heat Treatment Conditions

As a workpiece, the inner race of 6320 was used, which was the same as that used in the preceding experiment for measuring the dimension change. The heat treatment condition is as follows. A workpiece was heated at 850 °C for 50 min in an electric furnace and quenched in an oil bath. In order to clear the effect of the dimension control, the temperature of the oil bath and the retaining time were varied so that the temperature of a workpiece before auscutting might change as follows: 200 °C x 3.5 min at Nos. 1 and 2, 180 °C x 4 min at Nos. 3 and 4 and...
2. Cutting Conditions

The cutting conditions are shown below and the process drawing for the cutting operation is shown in Fig. 6. One side surface and a half of the inside surface were finished in the operation-1 (OP-1) using the tools ① and ②. After chucking the turned surface, the remaining surfaces were finished in OP-2 using the tools ③, ② and ③.

Cutting speed: \( V = 200 \text{ m/min} \)
Feed: \( f = 0.2 \text{ mm/rev} \)
Depth of cut: \( t = 1.5 \text{ mm} \) (the workpiece as ring-rolled is finished by one pass to the desired dimension)
Tool: black ceramic (circular with 12.7 mm diameter)
the rake angle (\( \alpha \) deg)
① \( \alpha = -6 \text{ deg} \) (tool for side surface)
② \( \alpha = -9 \text{ deg} \) (tool for inside surface)
③ \( \alpha = -8.5 \text{ deg} \) (tool for outside surface)
Cutting lubricant: dry

The reason that the black ceramic tool was used is that it was best for auscutting and the cemented carbide tool wore out more quickly. It is considered that the temperature of the tool tip becomes very high in auscutting though the hardness of supercooled austenite is relatively low such as HB230.

3. Setting Values

The setting values input to the dimension control system are as follows in this work. Because the adequate range of the temperature of a workpiece for auscutting is 170~230 °C, just above the \( M_s \) point in the case of the quenching temperature of 850 °C, the reference temperature was set at 200 °C by taking a mean temperature.

Reference temperature: \( 200 \text{ °C} \)
Correction factor of each tool (\( G \)):
\[ G_1 = 3.0 \text{ (corresponds to X of tool ①)} \]
\[ G_2 = 2.2 \text{ (corresponds to X of tool ②)} \]
\[ G_3 = 3.0 \text{ (corresponds to X of tool ③)} \]
\[ G_4 = 1.1 \text{ (corresponds to Z of tool ①, ②, ③)} \]
Emissivity of infrared thermometer (\( \varepsilon \)):
\[ \varepsilon_1 = 0.93 \text{ (on the surface before auscutting)} \]
\[ \varepsilon_2 = 0.45 \text{ (on the surface after auscutting)} \]

The correction factor \( G \) was calculated as explained precedently. For example, in case of machining the outside surface, it is \( 135.5 \times 2.2 \times 10^{-2} \approx 3.0 \times 10^{-3} \). \( G_3 = 3.0 \) means that the correction of 3.0 \( \mu \text{m} \) for the tool position was made per 1 °C of the temperature change. The emissivity \( \varepsilon \) of an infrared thermometer was different in the surface conditions before and after auscutting and was determined separately by using a thermocouple placed at surfaces.

4. Experimental Procedure

The experimental procedure for the dimension control is shown in Fig. 7. The experiment was conducted for 14 workpieces under the same cutting conditions. The dimension control was set separately for each workpiece and the calculated correction value was canceled out each time. The data on the temperature of a workpiece before and after auscutting were printed out. The dimensions of the workpiece were measured just after auscutting and measured again after being cooled to room temperature.

3. Experimental Results

The results of the measurements of the machined dimensions and the temperature of the workpiece before and after auscutting are shown in Fig. 8. The machined dimensions were measured at the outside and inside of the workpiece. O mark indicates the machined dimension just after auscutting. ● mark indicates the dimension after the workpiece had been cooled to room temperature subsequent to auscutting and the quench hardening was finished (hardness: HRC 64.5~65). I mark indicates the magnitude of the quench distortion.

The final dimension after being cooled to room temperature subsequent to auscutting fluctuates within the range of 0.05 mm at the inside and outside of the workpiece. It can be controlled easily within a tolerance of ±0.07 mm in the ordinary turning operation by this control system even if the temperature of the workpiece varies as much as 30 °C before auscutting. The quench distortion is not more than about 0.05 mm and much smaller than that of an ordinary quenched workpiece (0.1~0.15 mm) not containing the cutting operation. The temperature
of the workpieces after auscutting is almost the same as that before auscutting, when the tool wear is small. On the other hand, the temperature rise of 5 – 10 °C is observed after auscutting in the workpiece No. 7 since the tool wear becomes large.

IV. Discussion

1. Influence of Tool Wear on Finished Dimension

1. In the Case that the Amount of the Tool Wear is Small

As the result of the dimension control experiments for 14 workpieces, the fluctuation of the final dimension was within the range of 0.05 mm. Therefore, it was possible to obtain the desired dimension accuracy (an objective accuracy was within ±0.07 mm, the same as a tolerance of ±0.07 mm for the ordinary turning operation) by the control system compensating for the change in the temperature of the workpiece before auscutting. The tool wear after cutting 14 workpieces was 0.05 mm on the outside tool and 0.1 mm on the inside tool in a flank wear VB, and it was relatively small. In the case that the amount of the tool wear is small, it is possible to obtain sufficient dimension accuracy in a practical use by this dimension control system developed even if the temperature of the workpiece changes before the cutting operation.

Table 2 shows the comparison of the final dimension between the measured and calculated value.

<table>
<thead>
<tr>
<th>Workpiece No.</th>
<th>Workpiece temp. (°C)</th>
<th>Machining dimension (mm)</th>
<th>Final dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D_a</td>
<td>D_m</td>
<td>D_a − D_m</td>
</tr>
<tr>
<td>2</td>
<td>O. 135.62</td>
<td>I. 99.55</td>
<td>136.00 136.01 +0.01</td>
</tr>
<tr>
<td>4</td>
<td>O. 135.55</td>
<td>I. 99.51</td>
<td>136.00 136.00 0</td>
</tr>
<tr>
<td>6</td>
<td>O. 135.58</td>
<td>I. 99.53</td>
<td>135.58 136.02 +0.03</td>
</tr>
</tbody>
</table>

Table 2. Comparison of final dimension between measured and calculated value.

The quench distortion in the heat treatment for a quench hardening is within about 0.05 mm and the dimension accuracy is better than that of the workpiece quenched in the conventional process. In auscutting, it is possible to reduce the amount to be ground because the quench distortion due to heating and cooling is removed fully by machining. In concrete terms, while the amount to be ground is estimated to be about 0.4 mm in the conventional process, it was possible to reduce it to 0.2 mm by the auscutting with this dimension control system and consequently, the grinding efficiency was greatly improved.

2. In the Case that the Amount of the Tool Wear is Large

In order to investigate the effect of the dimension control in the case that the amount of the tool wear is large, auscutting for workpieces of Nos. 15 – 43 was performed subsequent to the above experiment without the tool change. The condition of the quench cooling was 3.5 min retaining in oil at 180 °C.

The final dimension at the outside and inside of the workpiece, the tool wear and the temperature rise of the workpiece (temperature after auscutting-temperature before auscutting) are summarized in Fig. 9. It was found that the final dimension at the outside and inside becomes small as the number of workpiece increases. The dimension change in workpieces of Nos. 1 ~ 43 is -0.06 mm at the outside and -0.18 mm at the inside. The influence of the tool wear on the outside diameter is less and it is possible to obtain the desired accuracy. On the other hand, the inside diameter is much influenced by the tool wear and its dimension change is more than the tolerance in the turning operation.

This phenomenon is explained as follows. The tool wear after auscutting of 43 workpieces is 0.2 mm on the outside tool and 0.3 mm on the inside tool in the flank wear

\[ V_b \times \tan \alpha \times 2 \]

= 0.2 \times \tan 8.5 \times 2 \approx 0.06 \text{ mm} \quad \oplus \text{ at outside}

and

\[ V_b \times \tan \alpha \times 2 \]

= 0.3 \times \tan 9 \times 2 \approx 0.10 \text{ mm} \quad \ominus \text{ at inside}.
On the other hand, as shown in Fig. 9, the temperature rise by cutting increases as the tool wear increases, and it becomes about 40 °C after auscutting of 43 workpieces. Its influence on the machining dimension is

\[ 135.5 \times 2.2 \times 10^{-5} \times 40 \approx 0.12 \text{ mm} \] at outside

\[ 99.5 \times 2.2 \times 10^{-5} \times 40 \approx 0.09 \text{ mm} \] at inside.

Because the final dimension is influenced by both the tool wear and the temperature rise, compared with the workpiece of No. 1, the workpiece of No. 43 is considered to be influenced as follows:

outside: \[ +0.06 - 0.12 = -0.06 \text{ mm} \]
inside: \[ -0.10 - 0.09 = -0.19 \text{ mm} \]

This value is in agreement with the measured data.

As a means of correcting the dimension in the case that the amount of the tool wear is large, it is also effective to compensate for the tool wear by detecting the position of the tool tip with various detectors as used in a conventional turning operation. Moreover, in auscutting, it is effective to estimate the tool wear by detecting the temperature rise of a workpiece because there is a nearly linear relation between the tool wear and the temperature rise during cutting operation as shown in Fig. 9.

2. Influence of Quenching Temperature on Finished Dimension

Figure 4 shows that a small difference is recognized in the final dimension after martensitic transformation according to the change of the quenching temperature, even if the cutting operation was performed at the same temperature. As this phenomenon is thought to be related to the amount of retained austenite (\( \gamma_R \)), the relation between the amount of the dimension change and that of \( \gamma_R \) was examined using other specimens, and the influence of the quenching temperature on the dimension change was examined as well.

The ring shaped specimens, which are 120 mm in outside diameter, 100 mm in inside diameter and 20 mm in width, were made from the bearing material (SUJ3) mentioned above. The dimension change at the outside of the specimens and the amount of the \( \gamma_R \) were measured after quenching. The latter value was given by the ratio of diffracted intensity of \( \gamma(220) \) and \( \alpha(211) \) with an X-ray apparatus.

The amount of the dimension change (expansion) and that of \( \gamma_R \) are shown in Fig. 10 in the case of a quenching temperature at 800 ~ 900 °C. The amount of expansion becomes maximum at the quenching temperature of 850 °C on the average value, while there is a quench distortion of about 0.1 mm. On the other hand, the amount of \( \gamma_R \) increases as the quenching temperature rises.

The structure of quenched bearing steel is composed of the mixed structure, martensite+\( \gamma_R \)+undissolved carbide. The carbon content dissolved in the matrix is changed by the quenching temperature. According to Sato and Nishizawa,\(^2\) the structure of carbide is \((\text{Fe-M})_6\text{C}\) in the steel of Cr less than 3 % and of Mn less than 3 %, and it is almost the same as that in carbon steel. Then, we may use the same equations as those in carbon steel.

The weight percent of carbon (\( \%C \)) dissolved in austenite or martensite is expressed in Eq. (2).\(^3\)

\[ \%C = \frac{C_T - 0.067V_e}{1 - 0.01V_e} \]

Fig. 9. Effect of tool wear on final dimension and temperature rise of workpiece.

Fig. 10. Effect of quenching temperature on dimension change and retained austenite (\( \gamma_R \)).
where, $\%C_r$: weight percent of carbon contained in steel

$V_r$: volume percent of cementite.

In the quenched structure, the amount of undissolved carbide was about 7.5%, 2%, and 0% respectively, when the quenching temperature was 825°C, 900°C, and 925°C. $\%C_r$ of the specimens used in this experiment was 1.02. From the value of $\%C_r$ dissolved in the matrix which was calculated with Eq. (2), the relation between the quenching temperature ($T_q$) and $\%C_r$ is given by

$$\%C = 0.0046T_q - 3.235 \quad (3)$$

According to Koistinen and Marburger, in the quenching of carbon steel or low alloyed steel, the amount of $\tau_R$ at room temperature (20°C) depends on the $M_s$ point of the material as given in Eq. (4).

$$\tau_R = \exp \left[ -0.011(M_s - 20) \right] \times 100 \quad (4)$$

Using the experimental data shown in Fig. 4, the $M_s$ point is expressed in Eq. (5) as a function of quenching temperature. Therefore, the amount of $\tau_R$ is expressed in Eq. (6) as a function of quenching temperature.

$$M_s = -T_q + 1020 \quad (5)$$

$$\tau_R = \exp \left[ -0.011(1000 - T_q) \right] \times 100 \quad (6)$$

The amount of $\tau_R$ is calculated at the range of $T_q$=800°-900°C with Eq. (6) and is shown in Fig. 10. These calculated data are in agreement with the measured values in this experiment.

According to Lement, in the quenching of carbon steel or low alloyed steel, the amount of the volume change, occurs in association with the phase change, from ferrite+cementite to martensite or to austenite is expressed in Eqs. (7) or (8) as a function of dissolved carbon content.

$$JV_w = 1.69 (\%C) \quad (7)$$

$$JV_r = -4.64 + 2.21 (\%C) \quad (8)$$

Therefore, the amount of the volume change $\Delta V$ by quenching is expressed in Eq. (9), and the dimension change $\Delta l$ is expressed by Eq. (10) using the size, $l$ of the specimen before quenching.

$$\Delta V = JV_w(100 - \tau_R) + JV_r \times \tau_R \quad (9)$$

$$\Delta l = l \times JV/\beta \quad (10)$$

By substituting Eqs. (3), (6) to (9) in Eq. (10), the amount of the dimension change is given as a function of quenching temperature. The calculated result in the case of $l$=120 mm is shown in Fig. 10. A maximum expansion is obtained at the quenching temperature of 840°C and is 0.14 mm. The fluctuation of the dimension change in the quenching temperature is small in practical use.

**V. Conclusions**

In the machining process called auscutting, in which the cutting operation is performed in supercooled austenite during quench cooling, the dimension change after the cutting process was examined quantitatively. On the basis of the contraction rate of supercooled austenite, which was obtained by the experiment, a dimension control system was designed by which the finished dimension can be adjusted accurately even when the temperature of a workpiece before auscutting is varied. The effectiveness of this method was proved by experiments.

The main results obtained are summarized as follows.

1. The thermal contraction rate of supercooled austenite during quench cooling in bearing steel of SUJ3 is $2.2 \times 10^{-5}/°C$.

2. The $M_s$ point changes according to the quenching temperature with a small change of the final dimension. The final dimension is determined by the amount of retained austenite and that of the volume expansion due to martensitic transformation. It gains the maximum value at the quenching temperature of 840°-850°C. But the fluctuation of the final dimension is negligibly small for bearing steel in practical use. Therefore, the final dimension ($L$) is expressed in the following equation using the machining dimension ($l$) and the temperature of a workpiece ($T$) before auscutting.

$$L = l(1.0077 - 2.2 \times 10^{-5} \times T)$$

3. In the case that the amount of the tool wear is small, the final dimension can be controlled precisely by the developed dimension control system which makes the compensation of the machining dimension for the dimension change predicted at each temperature of workpieces on the basis of the thermal contraction rate of supercooled austenite, even if the fluctuation of the temperature in workpieces before auscutting is about 30°C. As the quench distortion becomes sufficiently small, it is possible to reduce the amount to be ground to approximately half of that to be ground in a conventional process.

4. In the case that the amount of the tool wear is large, another method is necessary to compensate for the tool wear, as the dimension accuracy cannot be obtained because of the change in the position of the tool tip and the temperature rise of the workpiece. Under the circumstances, it is effective to estimate the amount of the tool wear by measuring the temperature rise of the workpiece.

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