INTRODUCTION
The stiffness of a grinding system consists of the stiffness of a grinding wheel support system, the stiffness of a workpiece support system and the contact stiffness between a grinding wheel and a workpiece. In a grinding system, elastic deformation occurs as a result of the action of normal grinding forces. These elastic deformations induce not only residual stock removal from the workpiece, but also machining errors.

In these stiffnesses of the grinding system, the stiffness of the grinding wheel support system and the stiffness of the workpiece support system are determined depending on the construction of each grinding machine. On the other hand, the contact stiffness between the grinding wheel and the workpiece varies the difference of the dressing lead or of the grinding condition. Therefore, the quantitative estimation of the contact stiffness is difficult. And, in the conventional grinding operation, vitrified grinding wheel and resinoid grinding wheel are applied as well known. However, the difference of the contact stiffness of vitrified grinding wheels and resinoid grinding wheels have never been investigated. And, contact stiffness taking into account of dressing condition has never also been investigated.

From such a viewpoint, this paper aims to quantify the contact stiffness of vitrified grinding wheels and resinoid grinding wheels, taking into account of the dressing condition. The contact stiffnesses of grinding wheel under the dressing leads are 0, 0.25, 0.5 and 1.0 mm/rev are measured. And, the contact stiffnesses of both wheels are compared.

CONTACT STIFFNESS BETWEEN GRINDING WHEEL AND WORKPIECE
Contact stiffness is the stiffness in contact area between a grinding wheel and a workpiece. And, the elastic deformation of the grinding wheel occurs as a result of the action of normal grinding force in this contact area.

Stiffness of the grinding wheel support system Ks

Elastic deformation of grinding system δ_res

Elastic deformation of wheel δ_w

Elastic deformation of table δ_t

Contact stiffness K_con

Stiffness of the workpiece support system Kw

FIGURE 1. Schematic diagram of horizontal grinding system

elastic deformation of the grinding wheel in the contact area cannot be immediately measured. Here, elastic deformation of the grinding operation system δ_res includes a deformation of the grinding wheel support system δ_s, a deformation of the workpiece support system δ_w and the deformation of the grinding wheel δ_con, as shown in Figure 1. So, if deformations of δ_res, δ_s and δ_w could be measured and/or calculated, the elastic deformation δ_con could also be calculated by subtracting δ_s and δ_w from δ_res. Here, δ_res can be measured, however, δ_s and δ_w cannot be measured. Therefore, as the first step, in order to obtain δ_s and δ_w, stiffness of a grinder is measured.

STIFFNESS OF THE GRINDER AND FROATING AMOUNT OF THE TABLE
Stiffness of a grinding wheel support system Ks and stiffness of a workpiece support system Kw indicating stiffness of a horizontal grinder, as
shown in Figure 1, cannot be directly obtained. So, separating the stiffness between table and spindle head, and the stiffness between spindle head and spindle tip, these stiffnesses were individually measured. Figure 2 shows measured results of both stiffnesses. The stiffness between table and spindle head was 69.3 N/μm, and the stiffness of spindle head and spindle tip was 108.5 N/μm. Since these stiffnesses are connected in series, the stiffness of horizontal grinder can be calculated as 42.3 N/μm. Therefore, from this stiffness and normal grinding force, the elastic deformation between table and spindle tip $\delta_s + \delta_w$ can be calculatedly obtained by Hooke’s law.

On the other hand, structure of table consists of sliding guide faces of V-flat shapes, where lubricating oil is applied. Here, grinder’s table is floated by the lubricating oil when table is moving. Therefore, in grinding operation, certain depth of cut is settled, however, actual depth of cut is larger than settled depth of cut by influence of the floating amount of the table. In order to obtain actual depth of cut, the floating amount of the table has to be measured before experiment.

Figure 3 shows measured results of relation among the acted force in the table, the table feed speed and the floating amount of the table. From this figure, it is known that, in case that the table feed speed is 4.2 m/min, the floating amount of the table $\delta_t$ is calculated by the following equation.

$$\delta_t = -0.015F + 2.58$$

**MEASURING METHOD OF CONTACT STIFFNESS**

In order to obtain the elastic deformation of grinding wheel between a grinding wheel and a workpiece, the elastic deformation of total grinding system $\delta_{es}$ was measured at first. Table 1 shows grinding condition. Used grinding wheels were vitrified wheels and resinoid wheels, and were dressed by the dressing leads 0, 0.25, 0.5 and 1.0 mm/rev. In grinding operation, the peripheral speed was 1800 m/min, the settled depth of cut was about 10 μm. Normal grinding force was measured by a force sensor located below the workpiece. Since one path grinding was carried out, a grooves with wheel width is generated on the workpiece surface. After grinding, in order to obtain the stock removal of workpiece, ground groove shape was measured by a contour measuring device.

**TABLE 1. The grinding condition**

<table>
<thead>
<tr>
<th>Grinding wheel</th>
<th>WA60K6V</th>
<th>WA60J6B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peripheral speed</td>
<td>1800m/min</td>
<td></td>
</tr>
<tr>
<td>Table feed speed</td>
<td>4.2m/min</td>
<td></td>
</tr>
<tr>
<td>Dressing lead</td>
<td>0, 0.25, 0.5, 1.0mm/rev</td>
<td></td>
</tr>
<tr>
<td>Dressing depth of cut</td>
<td>50μm</td>
<td></td>
</tr>
<tr>
<td>Settled depth of cut</td>
<td>10μm</td>
<td></td>
</tr>
<tr>
<td>Workpiece</td>
<td>SS400</td>
<td></td>
</tr>
</tbody>
</table>

**MEASURED RESULTS OF THE ELASTIC DEFORMATION OF GRINDING WHEEL**

![Figure 2: Measured results of stiffness of horizontal grinder](image-url)

![Figure 3: Relation between acted force in the table and floating amount of the table](image-url)
Figure 4 shows a measured result of ground surface of workpiece in case that dressing lead is 0.0 mm/rev for vitrified wheel. From this figure, it is known that ground surface is formed for wheel width. Here, in this figure, the actual depth of cut indicates the sum of the settled depth of cut and the floating amount of the table. The settled depth of cut can be measured by an electrical micrometer in operation. The floating amount of the table can be calculated by substituting measured normal force to equation (1). Therefore, from subtracting the stock removal of workpiece from the actual depth of cut, the elastic deformation of grinding system $\delta_{\text{res}}$ can be obtained. As shown in Figure 4, since the actual depth of cut is 11.0 $\mu$m, and the stock removal is 6.1 $\mu$m, the elastic deformation of grinding system $\delta_{\text{res}}$ is calculated as 4.9 $\mu$m. In such a same way, other condition's elastic deformations of grinding system are measured, and measured results are shown in Figure 5.

As shown in Figure 1, the elastic deformation of grinding wheel in contact area $\delta_{\text{con}}$ can be obtained by subtracting the elastic deformation between spindle and table $\delta_{s}+\delta_{w}$ from the total elastic deformation of grinding system $\delta_{\text{res}}$. 

![Figure 4. Measured results of elastic deformation of grinding wheel](image1)

![Figure 5. Relation between dressing lead and elastic deformation of grinding system](image2)

![Figure 6. Relation between dressing lead and normal grinding force](image3)

![Figure 7. Relation between dressing lead and elastic deformation of the grinding wheel area](image4)

![Figure 8. Relation between dressing lead and contact stiffness](image5)
Here, $\delta_s + \delta_w$ can be calculated by dividing the normal grinding force $F$ shown in Figure 6 by the stiffness between spindle and table $K_s + K_w$ shown in Figure 2. Therefore, by subtracting $\delta_s + \delta_w$ from $\delta_{res}$, the elastic deformation of the grinding wheel $\delta_{con}$ can be obtained, as shown in Figure 7.

CALCULATED RESULTS OF THE CONTACT STIFFNESS OF GRINDING WHEEL

Figure 8 shows calculated results of the contact stiffness of grinding wheel $K_{con}$ that is obtained by dividing the normal grinding force $F$ shown in Figure 6 by the elastic deformation $\delta_{con}$ shown in Figure 7. From this figure, it is known that the contact stiffness is greatest when the lead is 0.0 mm/rev, and smallest when the lead is 0.25 mm/rev. It is considered that the contact stiffness closely correlates with the number of abrasive grains on the grinding wheel surface [1] [2]. In this consideration, it is also known that, as shown in Figure 6, the normal grinding force is smallest when the lead is 0.25 mm/rev that regards as smallest number of grains on the wheel surface.

On the other hand, from results of the elastic deformation of grinding wheel shown in Figure 7, especially for vitrified wheels, it is known that the influence of the dressing lead variation is not large for the elastic deformation of grinding wheel. From this result, it can be considered that the residual stock removal of a workpiece is not affected by the difference of dressing lead.

CONTACT STIFFNESS FOR DIFFERENCE OF BOND

Comparing the contact stiffness of vitrified wheel with one of resinoid wheel, difference of the contact stiffness for both wheels is small. It is considered that this cause is that the contact stiffness of wheel $K_{con}$ varies with depending on the normal grinding force. Figure 9 shows relation between the normal grinding force and the contact stiffness when dressing lead is 1.0 mm/rev for vitrified and resinoid grinding wheels. From this figure, it is known that contact stiffness varies with the normal grinding force. Here, difference of contact stiffness for both wheels is not seen in Figure 8. However, as shown in Figure 9, it is known that the contact stiffness for both bonds vary. As shown in Figure 6, in case of the dressing lead 1.0 mm/rev, the normal grinding force for vitrified wheel was 60 N, and the normal grinding force for resinoid wheel was 100 N. Comparing contact stiffnesses for each normal force in Figure 9, it is known that both contact stiffness corresponds with at 34 N/\mu m. From above, since contact stiffness varies with normal grinding force, it can be considered that difference of contact stiffness for both grinding wheels shown in Figure 8 is not occurred in this area.

CONCLUSIONS

Contact stiffnesses of grinding wheel for vitrified and resinoid wheel were measured for different dressing lead. Results obtained in this study are summarized as follows;

- It is known that the contact stiffness depends on the number of abrasive grains on the wheel surface, and is smallest when dressing lead is 0.25 mm/rev.
- It is found that difference of the contact stiffnesses of vitrified wheel and resinoid wheel is small. However, it is caused by that contact stiffness varies with the normal grinding force.

REFERENCES