Physical Properties and Color Analysis of Dental Porcelain

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For the purpose of clarifying the color change in porcelains under different firing conditions, we have investigated the properties of porcelain materials, used for firing. Further, porcelain materials fired in a platinum furnace or an infrared furnace were used for analysis of color change.

Key Words: Heat Expansion, Color Analysis, Dental Porcelain

INTRODUCTION

As prosthodontic materials are generally used for the front teeth, they must necessarily possess an aesthetic element. Especially, tooth form, position, and size are the most important elements affecting the aesthetics of the mouth. Furthermore, color harmony with neighboring teeth and those in the opposite jaw, as well as with the lip, gingiva, and the facial tone, is important. Recently in order to select the color tone of the front teeth easily and quickly, the ready-made Shade Guide was developed, and the color tone is subjectively decided by its harmony with neighboring teeth. However, since color selection by the Shade Guide is subjective, there arise some differences due to the various conditions under which the color is measured and to differences in Lot No. between Shade Guide and porcelain powder. Moreover, differences in the furnace used for firing should not be neglected.

In this study, we investigated some properties of porcelain materials used for firing and objectively analyzed the color of the Color Table and porcelain powder which is unfired, and the color change of the porcelain materials fired in a platinum or infrared furnace.

MATERIALS AND METHODS

Porcelain materials used for firing were UNI BOND, CERA 8, VMK 68, and Pearlite 21. Four kinds of each of them—opaque, dentin, enamel, and transparent—were selected, as shown in Table 1. X-ray fluorescence analysis of porcelain materials used for firing was performed using an X-ray fluorescence spectrometer (Shimazu, Type VF-310). Standard and experimental samples were made as follows without pretreatment such as, pulverizing, heating, or dehydration: 0.7 g of sample was mixed with 7 g of lithium borate (Li₂B₂O₇, Wako Pure Chemical Industries, LTD.) and put into a platinum crucible (35 mmø), the samples were melted and kept at 1050 °C for 8 minutes. After removing the foam, the samples were allowed to cooled. They were then immediately measured with
COLOR ANALYSIS OF DENTAL PORCELAIN

Table 1  Porcelain materials used for firing and their abbreviation symbols.

<table>
<thead>
<tr>
<th>Porcelain materials</th>
<th>Shade No.</th>
<th>Lot No.</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
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<td>A0</td>
<td>U-O</td>
</tr>
<tr>
<td></td>
<td>BODY</td>
<td>A-B</td>
<td>U-B</td>
</tr>
<tr>
<td></td>
<td>INCISAL</td>
<td>57</td>
<td>U-I</td>
</tr>
<tr>
<td></td>
<td>TRANSPARENT</td>
<td>T</td>
<td>U-T</td>
</tr>
<tr>
<td>CERA B</td>
<td>OPAQUE</td>
<td>PO 531</td>
<td>C-O</td>
</tr>
<tr>
<td></td>
<td>DENTIN</td>
<td>A-D</td>
<td>C-D</td>
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<td></td>
<td>ENAMEL</td>
<td>558</td>
<td>C-E</td>
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<tr>
<td></td>
<td>TRANSPARENT</td>
<td>T 530</td>
<td>C-T</td>
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<tr>
<td>VITA VMK 68</td>
<td>OPAQUE</td>
<td>531</td>
<td>V-O</td>
</tr>
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<td>540</td>
<td>V-D</td>
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<td>Pearlite 21</td>
<td>OPAQUE</td>
<td>A1</td>
<td>J-O</td>
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<td>A1</td>
<td>J-B</td>
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<td>J-P</td>
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</table>

an X-ray fluorescence spectrometer and 40 seconds total c.p.s. were recorded at each spectrum (Kα, Lα1, or Lβ1) of each element. To measure heat expansion, we made the samples by the clinical method at the size of 4 mm×6 mm long. Samples, fired by each firing schedule, were measured under the following conditions: 0.7 g weight, 10°C/min. rising temperature, and ±50 μm sensitivity. Heat expansion curves were then calculated. For measuring color tone, the Color Table provided by the manufacturer was used. Pearlite 21 was not measured since a Color Table was not available. For measuring the color of unfired porcelain powder, basic magnesium carbonic acid (Kishida Kagaku, special grade) was mixed with the standard sample and fired for 10 hours at 1500°C in air. Magnesium carbonate (Basic) was utilized. 0.5 g of each standard sample and experimental sample was put into the cell (10 mm×3 mm height) and pressed by hand. A micro-multiphotometer (model MMP-1001 DP, Nippon Denshoku IND. Co., LTD.) was used to analyze the Color Table. For unfired porcelain powder and samples fired by a platinum or infrared furnace, micro-multiphotometer, and an UV-VIS-NIR recording spectrophotometer (model UV-360, Shimadzu IND. Co., LTD.) were utilized. The ULCS Color system L a b and the CIE Color system of R.S. Hunter were used to compare to colors. Samples fired by the platinum or infrared furnace were made by the same method used for making porcelain tooth. The firing method is shown in the firing schedule for each porcelain material. The size of the measuring sample was 15 mm×15 mm×1.5 mm.

RESULTS AND DISCUSSION

X-ray fluorescence values of porcelain materials for firing are shown in Table 2. In the case of UNI BOND porcelain materials, U-O porcelain contained less SiO₂ (54.00%),
Table 2 Composition of porcelain materials used for firing determined by X-ray fluorescence spectrometry

<table>
<thead>
<tr>
<th>Code</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>BaO</th>
<th>CaO</th>
<th>MgO</th>
<th>SnO₂</th>
<th>In₂O₃</th>
<th>ZrO₂</th>
<th>Fe₂O₃</th>
<th>TiO₂</th>
<th>V₂O₅</th>
<th>MnO</th>
<th>Cr₂O₃</th>
<th>Total</th>
</tr>
</thead>
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<td>8.90</td>
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<td>1.10</td>
<td>5.30</td>
<td>0.64</td>
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<td>1.02</td>
<td>0.00</td>
<td>1.050</td>
<td>1.00</td>
<td>0.30</td>
<td>0.25</td>
<td>0.00</td>
<td>98.36</td>
</tr>
<tr>
<td>U-B</td>
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<td>10.70</td>
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<td>2.00</td>
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<td>0.00</td>
<td>0.74</td>
<td>0.30</td>
<td>1.420</td>
<td>0.08</td>
<td>0.00</td>
<td>0.39</td>
<td>0.00</td>
<td>97.54</td>
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<tr>
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<td>10.30</td>
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<td>1.20</td>
<td>2.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.74</td>
<td>0.15</td>
<td>1.020</td>
<td>0.02</td>
<td>0.00</td>
<td>0.36</td>
<td>0.00</td>
<td>97.69</td>
</tr>
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<td>1.20</td>
<td>2.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.70</td>
<td>0.10</td>
<td>1.230</td>
<td>0.02</td>
<td>0.00</td>
<td>0.36</td>
<td>0.00</td>
<td>97.11</td>
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<tr>
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<td>0.94</td>
<td>5.36</td>
<td>0.00</td>
<td>27.08</td>
<td>0.088</td>
<td>0.07</td>
<td>0.03</td>
<td>0.00</td>
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<td>0.82</td>
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<td>0.74</td>
<td>1.03</td>
<td>0.034</td>
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<tr>
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<td>15.10</td>
<td>9.24</td>
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<td>3.58</td>
<td>1.37</td>
<td>0.43</td>
<td>0.04</td>
<td>1.07</td>
<td>0.78</td>
<td>0.033</td>
<td>0.45</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
<td>98.52</td>
</tr>
<tr>
<td>V-E</td>
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<td>3.67</td>
<td>1.38</td>
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<td>1.10</td>
<td>0.51</td>
<td>0.035</td>
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<td>V-T</td>
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<td>0.35</td>
<td>0.028</td>
<td>0.45</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
<td>98.13</td>
</tr>
<tr>
<td>J-O</td>
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<td>1.69</td>
<td>1.17</td>
<td>9.74</td>
<td>0.76</td>
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<td>0.026</td>
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<td>6.96</td>
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<td>0.16</td>
<td>0.75</td>
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<td>0.027</td>
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<td>0.01</td>
<td>89.58</td>
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<td>6.92</td>
<td>0.36</td>
<td>1.95</td>
<td>1.21</td>
<td>0.06</td>
<td>0.67</td>
<td>0.00</td>
<td>0.031</td>
<td>0.26</td>
<td>0.01</td>
<td>0.00</td>
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<td>98.35</td>
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<tr>
<td>J-T</td>
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<td>13.47</td>
<td>9.09</td>
<td>6.90</td>
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<td>1.92</td>
<td>1.28</td>
<td>0.04</td>
<td>0.77</td>
<td>0.00</td>
<td>0.028</td>
<td>0.26</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>99.69</td>
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</table>

Al₂O₃ (8.90%), K₂O (8.90%), Na₂O (6.10%), and BaO (1.10%) than U-B, -I, and -T materials. Only U-O porcelain contained, MgO (0.64%), SnO₂ (9.80%), and V₂O₅ (0.30%), while U-B, -I, and -T porcelain materials didn't contain any of these compounds. U-O porcelain didn't contain any ZnO₂, while U-B contained 0.30%, -I, 0.15%, and -T, 0.10%. U-B, -I, and -T porcelain materials didn't contain MgO, SnO₂, and V₂O₅, and U-O materials didn't contain ZrO₂. None of the UNI BOND materials contained Cr₂O₃.

In the case of CERA 8 porcelain materials, C-O porcelain materials contained less SiO₂ (37.14%), Al₂O₃ (9.05%), K₂O (5.26%), Na₂O (10.42%), CaO (0.09%), and In₂O₃ (0.00%) than C-D, -E, and -T porcelain materials. C-O porcelain contained a large amount of MgO (0.94%), SnO₂ (5.36%), ZrO₂ (27.08%), Fe₂O₃ (0.088%), V₂O₅ (0.03%), and Cr₂O₃ (0.06%). None of the CERA 8 porcelain materials contained BaO or MnO. C-O porcelain didn't contain any In₂O₃, and C-E and -T materials didn't have any ZrO₂. C-D, -E, and -T porcelains didn't contain any V₂O₅.

In the case of VMK 68 porcelain materials, V-O porcelain contained less SiO₂ (52.52%), K₂O (8.75%), BaO (1.30%), MgO (0.00%), and In₂O₃ (0.74%) than V-D, -E, and -I porcelains. The VMK 68 porcelains varied in their CaO and Fe₂O₃ contents, but none contained MnO or Cr₂O₃. V-O porcelain didn't contain any MgO.

In the case of Pearlite 21 porcelain materials, J-O porcelain contained less Na₂O (5.38%), BaO (0.00%), CaO (1.69%), MgO (1.17%), and Fe₂O₃ (0.026%) than J-B, -E, and -T porcelains. J-O porcelain contained more SnO₂ (9.74%), TiO₂ (2.03%), and V₂O₅ (0.11%) than J-B, -E, and -T porcelains. For SiO₂, J-O porcelain contained 58.87%; J-B, 58.04%; J-E, 64.75%; and J-T, 65.58%. J-O porcelain had no BaO or Cr₂O₃. None of the Pearlite 21 porcelain materials contained ZrO₂ or MnO.

Generally potassium felspar (K₂O·Al₂O₃·6SiO₂) is used as the raw material for dental porcelain materials. The theoretical chemical content of it is 64.72% SiO₂, 18.35% Al₂O₃,
and 16.93% K₂O. A part of the potassium is often exchanged for Na, Ca, or Fe. This K₂O·Al₂O₃·SiO₂ system has a Leucite composition and K₂O affects the heat expansion by Leucite production, which is the most important factor for porcelain materials. As the rate of heat expansion of Leucite is 20×10⁻⁶/°C, it is impossible to make porcelain materials, whose heat expansion coefficient is similar to the alloy for firing, by adjusting the Leucite content. By increasing the content of K₂O, the composition ratio of porcelain material becomes similar to that of Leucite, and crystallization occurs easily. In the case of UNI BOND porcelain materials, U-O porcelain has a K₂O content of 8.89%, while U-B, -I, and -T porcelains have a content of 10.70%, 10.30%, and 10.10%, respectively. Compared with other porcelain materials, the K₂O content of UNI BOND is the highest. The more the K₂O content increases, the more its composition of the porcelain approaches that of Leucite and the more easily it crystallizes. Especially when TiO₂ is present, which initiates crystal core formation, this tendency becomes clear. However, TiO₂ and ZrO₂ are non-transparent agents which can be employed to regulate the transparency by using the difference of reflection rate in order to imitate to the natural teeth's feature. So, in proportion to increasing of K₂O content, if TiO₂ and ZrO₂ contents are increased, the non-transparency of porcelain materials becomes too high. In the case of UNI BOND porcelain materials, the K₂O content is higher than that of the other porcelains, and the TiO₂ and ZrO₂ contents are lower than those for the others. In the case of CERA 8 porcelain materials, the firing temperature is 790°C, which is low. The composition is K₂O and Na₂O as an alkali flux, with the Na₂O content being characteristic ally high (10.42–14.46%). When the Na₂O content increases, the rate of heat expansion of the porcelain material also increases. Alkali metal oxides, like lithium and potassium, also have a similar effect. The Na₂O content in CERA 8 porcelain materials is high. In₄O₃, which is concerned with the bonding between metal and porcelain, is not present in C-O porcelain. Instead of it, C-O contains 5.36% SnO₂, and also 27.08% ZrO₂ as a non-transparent agent. In the case of VMK 68 porcelain materials, the V-O type has an SnO₂ content of 0.21% and that of In₂O₃ is 0.74%, which is less than in other porcelain materials.

As Table 3 shows, VMK 88 porcelain material contains 2.36% SnO₂, which is 2.15% higher than the value for ZrO₂ in VMK 68 porcelain materials, as a non-transparent re-agent was not contained in any of the Pearlite 21 porcelain materials.

Table 3  X-ray fluorescence spectrometric quantitative values of Vita VMK 88 porcelain material

<table>
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<tr>
<th></th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>BaO</th>
<th>CaO</th>
<th>MgO</th>
<th>SnO₂</th>
<th>In₂O₃</th>
<th>ZrO₂</th>
<th>Fe₂O₃</th>
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<th>V₂O₅</th>
<th>MnO</th>
<th>Cr₂O₃</th>
<th>Cr₃O₄</th>
<th>total</th>
</tr>
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<tbody>
<tr>
<td>%</td>
<td>53.20</td>
<td>18.78</td>
<td>8.44</td>
<td>6.41</td>
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<td>1.56</td>
<td>0.04</td>
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<td>0.030</td>
<td>7.82</td>
<td>0.04</td>
<td>0.03</td>
<td>0.00</td>
<td>98.82</td>
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Figures 1–4 show the heat expansion curves of each porcelain material, and Table 4 shows their heat expansion coefficients at each temperature. Figure 1 shows the heat expansion curve of UNI BOND porcelain material. The U-O porcelain has a transition point near 550°C, but it is unclear and shows linear expansion. Its softening point is 630 °C, with an expansion rate of 0.83%. The heat expansion coefficient of U-O porcelain is 14.6×10⁻⁶/°C from 100 to 600°C. U-B porcelain material has a smooth transition point
Table 4  Heat expansion coefficients of porcelain materials used for firing at each temperature range

<table>
<thead>
<tr>
<th>Code</th>
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<th>300-500 °C</th>
<th>500-700 °C</th>
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<td></td>
</tr>
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<td>C-T</td>
<td>13.0</td>
<td>10.0</td>
<td>11.5*</td>
<td></td>
</tr>
<tr>
<td>V-D</td>
<td>11.4</td>
<td>15.1</td>
<td>12.7</td>
<td></td>
</tr>
<tr>
<td>V-E</td>
<td>11.9</td>
<td>14.2</td>
<td>12.9</td>
<td></td>
</tr>
<tr>
<td>V-I</td>
<td>13.0</td>
<td>14.5</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>J-O</td>
<td>11.5</td>
<td>14.0</td>
<td>15.7</td>
<td></td>
</tr>
<tr>
<td>J-H</td>
<td>11.5</td>
<td>12.5</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>J-E</td>
<td>11.0</td>
<td>13.5</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>J-T</td>
<td>11.0</td>
<td>12.5</td>
<td>11.8</td>
<td></td>
</tr>
</tbody>
</table>

*: values measured from 100°C to 500°C

Figure 1  Heat expansion curves of UNI BOND porcelain materials.

near 550°C, and U-I porcelain material is similar. Their softening points are 680°C and 650°C, respectively, and their heat expansion rates are 0.90% and 0.82%, respectively. The heat expansion coefficients of U-B and -I porcelains are $13.8 \times 10^{-6} / ^\circ C$ and $13.3 \times 10^{-6} / ^\circ C$, respectively. The softening point of U-T porcelain is near 550–600°C, and its heat
COLOR ANALYSIS OF DENTAL PORCELAIN

Figure 2  Heat expansion curves of CERA 8 porcelain materials.

Figure 3  Heat expansion curves of VMK 68 porcelain materials.
expansion rate is 0.72%. The heat expansion coefficient of this porcelain material is $13.0 \times 10^{-6}/°C$.

Figure 2 shows the heat expansion curve of CERA 8 porcelain materials. In the case of C-O porcelain, the transition point is near 450°C; the softening point, near 530–570°C; and the heat expansion coefficient, $11.5 \times 10^{-6}/°C$ from 100 to 500°C. In the case of C-D porcelain material, the transition is unclear. Its softening point is near 520–560°C, and the heat expansion coefficient is $11.5 \times 10^{-6}/°C$. C-O porcelain material gave the same values. In comparing C-E and -T porcelain materials, their curves tend to be similar to each other. Their transition points were near 520°C and 460°C, and their heat expansion coefficients, $12.7 \times 10^{-6}/°C$ and $11.5 \times 10^{-6}/°C$, respectively.

Figure 3 shows the heat expansion curves of VMK 68 porcelain materials. For V-O porcelain material, the transition point was near 550°C, and the heat expansion coefficient was 0.76%. Its softening point was 830°C, with a heat expansion rate of 1.36%. Its heat expansion coefficient from 100–600°C was $16.6 \times 10^{-6}/°C$. Both V-D and -E porcelain materials gave similar heat expansion curves. Both of them had a transition point at 580°C and a 0.66% heat expansion rate. The softening point was at 660°C, and heat expansion rate was 0.78% and 0.80%. Their heat expansion coefficients were $12.7 \times 10^{-6}/°C$ and $12.9 \times 10^{-6}/°C$, respectively. The V-I porcelain material had a transition point near at 480°C and a softening point from 650°C to 680°C. Its heat expansion rate was 0.75%, with a coefficient of $12.6 \times 10^{-6}/°C$.

Figure 4 shows heat expansion curves for Pearlite 21 porcelain materials. J-O porcelain material had a transition point at near 630°C, and its softening point was from 660–700°C. Its heat expansion rate was 0.76%, and the coefficient was $15.7 \times 10^{-6}/°C$ from 100°C to 600°C. For the J-B porcelain the transition point was near 550°C; the softening point, from 650°C to 670°C; the heat expansion rate, 0.71%; and the heat expansion
coefficient, $12.0 \times 10^{-6}/\degree C$. For J-E porcelain material, the transition point was $550\degree C$, and the heat expansion rate was $0.66\%$. Its softening point was from $630\degree C$ to $670\degree C$. The heat expansion coefficient was $13.2 \times 10^{-6}/\degree C$. J-T porcelain had a transition point at $550\degree C$, which was the same as for J-B porcelain. Its softening point was from $610\degree C$ to $660\degree C$; and its heat expansion rate was $0.65\%$, with a coefficient of $11.8 \times 10^{-6}/\degree C$.

Table 6 shows L, a, and b values of unfired powder of UNI BOND, CERA 8, VMK 68, and Pearlite 21 porcelain materials.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
UNI BOND & A : O & A : B & 57 & T & POS581 A : D E 558 T 530 CERA 8 \\
\hline
77.24 & 54.84 & 51.51 & 51.53 & L & 80.69 & 64.21 & 46.85 & 48.45 \\
(0.790) & (0.201) & (1.391) & (1.306) & a & 0.518 & (1.231) & (0.675) & (1.596) \\
1.44 & -0.17 & -0.16 & 0.43 & & 2.73 & -0.15 & 0.97 & 1.46 \\
(0.127) & (0.124) & (0.114) & (0.086) & b & 0.125 & (0.050) & (0.124) & (0.075) \\
14.34 & 8.13 & 2.47 & 5.49 & & 15.71 & 7.64 & 4.07 & 3.70 \\
(0.200) & (0.298) & (0.186) & (0.278) & & 0.308 & (0.297) & (0.228) & (0.423) \\
\hline
VMK 68 & 531 & 540 & 558 & 530 & & & & \\
79.69 & 53.57 & 37.62 & 26.29 & L & 91.97 & 95.11 & 97.05 & 99.19 \\
(0.233) & (0.436) & (0.684) & (0.515) & a & (0.186) & (0.171) & (0.356) & (0.168) \\
1.24 & -0.90 & -0.36 & 0.09 & & 0.61 & 3.82 & -0.15 & 0.23 \\
(0.248) & (0.048) & (0.072) & (0.062) & b & (0.048) & (0.128) & (0.038) & (0.024) \\
16.09 & 5.38 & 1.68 & 0.13 & & 9.43 & 4.75 & -1.33 & -0.02 \\
(0.145) & (0.291) & (0.214) & (0.178) & & (0.078) & (0.057) & (0.199) & (0.098) \\
\hline
\end{tabular}
\caption{L, a, and b values measured from the COLOR TABLE of UNI BOND, CERA 8, and VMK 68 porcelain materials.}
\end{table}

Table 6 shows L, a, and b values measured for unfired porcelain material powder of UNI BOND, CERA 8, VMK 68, and Pearlite 21 porcelain materials.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|}
\hline
UNI BOND & A : O & A : B & 57 & T & POS581 A : D E 558 T 530 CERA 8 \\
\hline
92.23 & 95.85 & 96.20 & 99.15 & L & 91.97 & 95.11 & 97.05 & 99.19 \\
(0.288) & (0.186) & (0.074) & (0.164) & a & (0.186) & (0.171) & (0.356) & (0.168) \\
0.51 & 6.58 & -0.27 & -0.30 & & 0.61 & 3.82 & -0.15 & 0.23 \\
(0.045) & (0.133) & (0.022) & (0.033) & b & (0.048) & (0.128) & (0.038) & (0.024) \\
8.81 & 1.19 & -2.60 & -0.06 & & 9.43 & 4.75 & -1.33 & -0.02 \\
(0.186) & (0.063) & (0.014) & (0.126) & & (0.078) & (0.057) & (0.199) & (0.098) \\
\hline
93.47 & 94.79 & 95.20 & 99.37 & L & 90.83 & 96.62 & 90.30 & 93.83 \\
(0.380) & (0.465) & (0.224) & (0.249) & a & (0.208) & (0.212) & (0.074) & (0.089) \\
1.25 & 3.56 & -0.35 & 0.18 & & 0.26 & 0.02 & 1.16 & 2.40 \\
(0.070) & (0.258) & (0.012) & (0.022) & b & (0.059) & (0.026) & (0.036) & (0.072) \\
9.04 & 5.31 & -0.82 & 0.98 & & 3.64 & 2.51 & -6.36 & 11.08 \\
(0.254) & (0.253) & (0.192) & (0.040) & & (0.151) & (0.070) & (0.076) & (0.102) \\
\hline
\end{tabular}
\caption{L, a, and b values measured for unfired porcelain material powder of UNI BOND, CERA 8, VMK 68, and Pearlite 21 porcelain materials.}
\end{table}

68, and Pearlite 21 porcelain materials. In the case of UNI BOND and CERA 8 porcelain materials, their L, a, and b values were similar. The a value of U-I porcelain material was $-0.27$ (0.022). J-E porcelain material was $1.16$ (0.036), and it showed a strong red
tendency. The \( a \) and \( b \) values of UNI BOND porcelain material were \(-0.30 (0.033)\) and \(-0.06 (0.126)\). For V-I porcelain, they were \(0.18 (0.022)\) and \(0.98 (0.040)\). And for J-E and -T porcelains, they were \(2.40 (0.072)\) and \(11.08 (0.102)\). The \( a \) values indicated a strong red tendency; and the \( b \) values, a strong yellow one.

Comparing the \( L \), \( a \), and \( b \) values of the Color Table (Table 5) with the samples fired in the platinum furnace (Table 7), the \( b \) value of U-O porcelain, \(2.47 (0.186)\) in the Color Table, shows a blue tendency against that of \(-0.37 (0.124)\) in samples fired in the platinum furnace. For U-T porcelain, the \( L \), \( a \), and \( b \) values in the Color Table were \(51.53 (1.306), 0.43 (0.086), \) and \(5.49 (0.278)\) respectively compared with the corresponding values obtained for samples fired in the platinum furnace, which were \(26.29 (0.515), 0.09 (0.062), \) and \(0.13 (0.178)\) respectively. They were all low values. The \( L \) value indicated a strong dark tendency; the \( a \) value, a green tendency; and the \( b \) value, a blue one. In the case of CERA 8 porcelain materials \( L \), \( a \), and \( b \) values, there was not much difference between the Color Table and samples fired in the platinum furnace. In the case of V-D porcelain material, the \( b \) value of the sample fired in the platinum furnace was \(-0.71 (0.205)\), indicating a blue tendency compared with the \( b \) value of the Color Table, \(0.38 (0.291)\). In the case of V-I porcelain material, the \( a \) value of the platinum furnace-fired sample was \(-0.40 (0.000)\), and it shows a green tendency compared with that of the Color Table, \(0.09 (0.062)\). In the case of J-E porcelain material, the \( b \) value of samples fired in the platinum furnace was \(-0.70 (0.170)\), indicating a blue tendency, compared with that of the Color Table, \(1.68 (0.214)\). In the case of J-T porcelain material, the \( a \) value of samples fired in the platinum furnace was \(-0.76 (0.046)\), showing a green tendency compared with that of the Color Table, \(0.09 (0.062)\). The \( b \) value of samples fired in the platinum furnace was \(-2.84 (0.131)\) compared with that of the Color Table, \(0.13 (0.178)\), thus showing a blue tendency.

### Table 7: \( L \), \( a \), and \( b \) values measured for UNI BOND, CERA 8, VMK 68, and Pearlite 21 porcelain materials fired in a platinum furnace

<table>
<thead>
<tr>
<th>UNI BOND</th>
<th>( L )</th>
<th>( a )</th>
<th>( b )</th>
<th>( T )</th>
<th>( T )</th>
<th>( T )</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>82.88</td>
<td>55.36</td>
<td>48.35</td>
<td>37.88</td>
<td>( 81.33 )</td>
<td>( 54.29 )</td>
<td>( 44.70 )</td>
<td>( 37.72 )</td>
</tr>
<tr>
<td>( 0.809 )</td>
<td>( 0.967 )</td>
<td>( 0.478 )</td>
<td>( 0.922 )</td>
<td>( 0.509 )</td>
<td>( 1.109 )</td>
<td>( 2.507 )</td>
<td>( 1.348 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VMK 68</th>
<th>( L )</th>
<th>( a )</th>
<th>( b )</th>
<th>( T )</th>
<th>( T )</th>
<th>( T )</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>83.82</td>
<td>58.34</td>
<td>57.83</td>
<td>47.28</td>
<td>( 78.75 )</td>
<td>( 55.32 )</td>
<td>( 51.51 )</td>
<td>( 48.23 )</td>
</tr>
<tr>
<td>( 0.672 )</td>
<td>( 0.937 )</td>
<td>( 0.346 )</td>
<td>( 0.017 )</td>
<td>( 0.838 )</td>
<td>( 0.250 )</td>
<td>( 0.462 )</td>
<td>( 0.620 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pearlite 21</th>
<th>( L )</th>
<th>( a )</th>
<th>( b )</th>
<th>( T )</th>
<th>( T )</th>
<th>( T )</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>531.00</td>
<td>540.00</td>
<td>558.00</td>
<td>530.00</td>
<td>( 14.93 )</td>
<td>( 2.64 )</td>
<td>( -0.71 )</td>
<td>( -2.64 )</td>
</tr>
</tbody>
</table>
Comparing the L, a, and b values of the Color Table (Table 5) with those of samples fired in the infrared furnace (Table 8), the b value in the Color Table for U-I porcelain was 2.47 (0.186), while the value for the sample fired in the infrared furnace was −1.12 (0.069). This low value indicates a blue tendency. In the same way, the a value for the U-T porcelain material was −0.35 (0.060), showing a green tendency, compared with the a value of the Color Table, 0.43 (0.086). The b value of the sample was −0.49 (0.102) compared with the b value of the Color Table, 5.49 (0.278), indicating a blue tendency. In the case of the C-E porcelain material, the a value of the sample was −0.20 (0.075), showing a green tendency, compared with the a value of the Color Table, 0.97 (0.124). In the case of C-T porcelain, the a value of the sample was −0.11 (0.061), showing a green tendency compared with that of the Color Table, 1.46 (0.075). In the case of V-D porcelain material, the b value of the sample was −0.79 (0.108), compared with that of Color Table, 5.38 (0.291). This shows that the sample fired in the infrared furnace had a blue tendency. In the case of V-I porcelain material, the a value of the sample was −0.50 (0.023) compared with that of the Color Table. It also shows that the sample fired in the infrared furnace had a low value, indicating a green tendency, compared with the Color Table. In the case of J-T porcelain, the a value of the sample was −0.85 (0.104), showing a green tendency compared with that of the Color Table, 0.09 (0.062). In the case of J-E and -T porcelains, the b values of the samples were −0.99 (0.333) and −0.323 (0.233), respectively, compared with those of the Color Table, 1.68 (0.214) and 0.13 (0.178), respectively. Both of them showed a blue tendency.

Comparing the L, a, and b values of V-T samples fired in the platinum furnace (Table 7) with those of samples fired in the infrared furnace (Table 8), the b value of the sample fired in the platinum furnace was 0.07 (0.091), showing a red tendency. On the other hand, that of the sample in the infrared furnace was −0.49 (0.102), tending toward the
blue. In the case of C-E and -T porcelains, the a values of samples fired in the platinum furnace were 0.16 (0.079) and 0.03 (0.099), respectively; whereas, those of samples fired in the infrared furnace were −0.20 (0.075) and −0.11 (0.061), respectively, showing a green tendency.

These color tendencies were seen in spectrophotometric curves of porcelain materials fired in the platinum or the infrared furnace as Figures 6 and 7 show.

Table 9 shows values calculated from the spectrophotometric curves shown in Figures 5–7. Y% indicates lightness; Pe(%), purity; λ nm, dominant wavelength; and W, whiteness. In the case of U-T porcelain material, there was little difference between platinum and infrared furnace-fired porcelain. In the case of C-E and -T porcelains, measured values of lightness were 45.3 and 49.0, respectively, for samples fired in the platinum furnace. The other hand, those fired in the infrared furnace were low, being 27.4 and 18.6, respectively. This was because CERA 8 porcelain material has the lowest melting point among the materials examined. From Table 2, which shows X-ray fluorescence spectrometric data, the Na₂O content of CERA 8 was shown to be 10.42–14.46% (from opaque to transparent), which was the highest among the compounds present. So, the more the Na₂O content increases, the more Si-O-Si bridge bonds are destroyed, and the melting point thus decreases like K₂O and B₂O₃. Na₂O is included to improve such properties as transparency, viscosity, and endurance. But oxides, like K₂O, CaO, Al₂O₃, and B₂O₃,
Table 9  Values of lightness, purity, dominant wavelength, and whiteness of porcelain powder used for firing and their samples (fired in a platinum furnace or in an infrared furnace) as measured by spectrophotometry

<table>
<thead>
<tr>
<th>Porcelain material</th>
<th>unfired porcelain material</th>
<th>porcelain material fired in the platinum furnace</th>
<th>porcelain material fired in the infrared furnace</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y%</td>
<td>Pq%</td>
<td>λnm</td>
</tr>
<tr>
<td>UNI BOND A:O</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>86.5</td>
<td>9.0</td>
<td>583.0</td>
</tr>
<tr>
<td></td>
<td>A:B</td>
<td>93.7</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>57</td>
<td>96.1</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>99.9</td>
<td>0.8</td>
</tr>
<tr>
<td>CERA 8</td>
<td>PO 531</td>
<td>86.7</td>
<td>9.6</td>
</tr>
<tr>
<td></td>
<td>A:D</td>
<td>92.4</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>E 558</td>
<td>94.6</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>T 530</td>
<td>100.0</td>
<td>0.8</td>
</tr>
<tr>
<td>VMK 8</td>
<td>531</td>
<td>87.7</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>540</td>
<td>98.9</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>558</td>
<td>90.3</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>530</td>
<td>93.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Pearlite 21</td>
<td>O:Al</td>
<td>81.0</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>D:Al</td>
<td>92.3</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>E:El</td>
<td>81.3</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
<td>E:TE</td>
<td>89.4</td>
<td>12.3</td>
</tr>
</tbody>
</table>

Figure 6  Spectrophotometric curves of porcelain materials fired in a platinum furnace.
are also effective. Generally, the methods for carrying out colorimetry are still not established. When the color of a porcelain material sample is measured, various factors affect the measured value, such as the sample size, thickness, particle size, conditions used for making the porcelain, sample surface, and lighting conditions. In the case of reflected light, the sample is measured on a white or black board. Horibe et al. reported a quantitative measuring method for transparency, considering that there arises individual differences between color measuring methods of opacity in Dental Silicate Cement. Light is directed at a 45° angle toward the sample, and the reflected light is measured at a 90° angle by using a photoelectric cell. When the intensity of the reflected light on the white board (MgO vapor is attached) is taken as 100%, and that on the black board as 0%, good results are obtained from the following formula:

\[ T(\%) = 10\sqrt{W - B} \]

- **T**: Transparency
- **W**: Diffusion and reflected light's intensity on the white board.
- **B**: Diffusion and reflected light's intensity on the black board.

Judging from Tables 5–8, there is obviously little difference in L, a, and b values. So, when the color of the natural tooth is decided, the person preparing the prosthodontic material should use the Shade Guide which is made by himself, using the same Lot No. of
porcelain material powder as the porcelain prothodontic sample instead of using the ready-made Shade Guide. Also it is better to always use the same furnace. If the porcelain powder or the furnace is changed, it is best to make another Shade Guide. By doing as this, the best prothodontic material, which has good color, may be made.

**CONCLUSIONS**

On the basis of the properties observed for porcelain powders used for firing and by analysis of the color change of the porcelain materials fired in a platinum or infrared furnace, the following results were obtained:

1. The SiO$_2$ content of the opaque type of each porcelain material ranged from 37.14\% (CERA 8) to 58.87\% (Pearlite 21), and that of the dentine, enamel, incisal types was 10–20\% in excess of the value for the opaque. The SiO$_2$ content of CERA 8 porcelain material was less than the others. The Al$_2$O$_3$ content was 17.05\% in VMK 68 porcelain material and 18.78\% in VMK 88 porcelain material. Compared with them, the content in the opaque type of UNI BOND porcelain material was only 8.90\%. K$_2$O and Na$_2$O tend to lower the melting point. The Na$_2$O content was less than the K$_2$O content for most of the porcelain materials, except for CERA 8, which was more (10.42–14.46\%). The SnO$_2$ content, which is concerned with bonding of the porcelain to the metal surface, was 0.21\% in the opaque type of VMK 68 porcelain material. In VMK 88 porcelain material, it was 2.36\%. The ZrO$_2$ content, which is a non-transparency-inducing reagent, was 27.08\% in CERA 8, which is a lower-melting porcelain material. It was much.

2. The heat expansion coefficients of the porcelain materials for firing ranged from 12.0–16.6×10^{-6}/°C from 100°C to 600°C. The transition point was 500–600°C, and its expansion rate was 0.6–0.76\%. The softening point was 610–830°C, with an expansion rate of 0.73–1.36\%. In CERA 8 porcelain material, these values differed from the others because CERA 8 is a lower-melting porcelain material. The heat expansion coefficient from 100°C to 500°C was 11.5–12.7×10^{-6}/°C. The transition point was 450–520°C, with an expansion rate of 0.40–0.59\%, and the softening point was 530–560°C, whose expansion rate was 0.52–0.66\%.

3. In comparing the samples fired in the platinum furnace with those fired in the infrared furnace, only the b value of UNI BOND porcelain material from the infrared furnace was high, 4.81 (0.102), compared with that from the platinum furnace, 4.44 (0.305). As for the other measured values, L, a, and b values of samples fired in the infrared furnace were lower. For CERA 8 porcelain materials, L, a, and b values of samples fired in the infrared furnace were all lower values. For VMK 68 porcelain material, the a value of dentin and the b value of incisal samples fired in the infrared furnace were higher, −0.32 (0.041), than those fired in the platinum furnace, −0.43 (0.030). For all the other measured values, samples fired in the infrared furnace showed low values. For infrared furnace-fired Pearlite 21 porcelain material, the b value of the opaque type, the L and b values of the dentin and body type, and the L value of enamel and incisal-(EI) showed high values. The other measured values of materials fired in the infrared furnace were lower.
There were some differences in color between the Color Table and the actual fired samples. There were also some color differences between samples fired in the platinum furnace and those fired in the infrared furnace.

REFERENCES

アルミ・ブロンズの腐食と変色

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アルミ・ブロンズ（銅・アルミニウム合金）は、工業方面では海水耐食性を要求される部品などに用いられており、歯科においては、鍛造用合金としてヨーロッパ、アメリカ合衆国、南アメリカ、アジアなどで市販されている。これらを対象とする組成として、工業用アルミ・ブロンズのなかから、CDA 955（Cu-Al-Ni-Fe）と CDA 956（Cu-Al-Si）をとりあげ、電気化学的腐食挙動と変色傾向を調べた。電気化学的腐食挙動の測定は、リソルベット液中の 10 分の 1 濃度のリソルベット液を用いて行ない、腐食電位、腐食電流、腐食抵抗、オーバル定数を得た。これらの値や分極曲線、合金間に大きな差は認められなかったが、塩素イオン濃度の影響を大きく受けた。変色試験は、Tuccillo and Nielsen の方法に従って 1 ヶ月硫酸ソーサ溶液中で実験した。変色の程度は、CDA 955 の方が大きく、合金間の差は著しかった。CDA 956 は、金合金、銀・パラジウム合金よりは変色したが、ステンレス鋼と同程度であり、CDA 955 は、アルファスチルシルコーン・ブロンズと同程度であった。

金属焼付陶材の焼成後の残留応力について

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金属焼付陶材の機械的性質は試験材の熱膨張係数、熱脹率、機械的強度、形状、表面の接着強さおよび変換する。とき、熱膨張係数と弾性係数は各材料の強さと同様に重要な因子である。

材料の適性に関する問題を明らかにするために、3 層よりなる平板模型を利用して金属焼付陶材の残留応力と変形を梁の理論を適用して明らかにした。また、合金の弾性係数が異なる 2 つの場合に対する検討から、高金属性合金および非高金属性合金を焼成した後に残留応力ないしの残留応力、変形の違いについて調べた。その結果、焼成後の残留応力、変形は非高金属性合金の方が大きくなくなったことがわかった。したがって、非高金属性合金では表面応力層が金属系合金よりも金属焼付陶材の焼成に際し重要な問題になる。とくに、その熱膨張係数と弾性係数が重要であることがわかった。また、陶材の熱膨張係数が金属の熱膨張係数よりも若干小さいことが適合性の点から好ましいことが明らかにされた。

焼付用陶材の諸物性と色彩

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焼付用陶材粉末の諸性質を調べるとともに、これらの観点から白金炉および外炉によって作製された陶材焼成物の色調変化を客観的に測定したところ、白金炉焼成物と赤外線焼成物の色調変化を比較し、U-B 陶材の b 値のみ赤外線焼成物が 4.44 (0.305) に対して 4.81 (0.102) と高く、他の測定値はすべて赤外線焼成物の方が L, a, b 値において低値を示した。C 陶材の L, a, b 値は、すべて測定値において、低値であった。V-D 陶材の a 値と V-I 陶材の b 値が白金炉焼成物の 0.43 (0.030) に対し、-0.32 (0.041) と赤外線焼成物が高値を示し、他の測定値はすべて赤外線焼成物の方が低値を示した。J-O 陶材の b 値と J-B 陶材の L, b 値および J-E 陶材の L
サイクリック・クリープのコンピューターシミュレーション

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臨床で認められているように，義歯床の破壊の大きな原因の一つは疲労である。これを究明するために，著者らはサイクリック・クリープ・テストを設計製作し，その試験結果を通じ報告した。

さらに本研究では，サイクリック・クリープの数値解析として，FEM を基にしたシミュレーションを開発し，パーソナルコンピュータを使用してシミュレーションを行った。

各種金属用アマルガムアロイの特性と，
練和時間がその物理的諸性質に及ぼす影響

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入手可能な低，高銅型アマルガムアロイの物理的諸性質を主として A. D. A. 規格 No. 1 の方法によって測定してその特性を比較，考察した。同時に，練和時間の変化がこれらの物理的諸性質に及ぼす影響についても検討した。

低銅型アロイにおいては粒状が物理的諸性質に及ぼす影響は比較的小さかったが，高銅型アロイでは著明であった。即ち，球状粒子のみで構成されている単一組織型高銅アロイは他のすべてのアロイに比べて相立った特徴を示した。即ち，低銅型アロイは勿論，配合型高銅アロイも明らかに異なった特徴を有ることがわかった。

練和時間が物理的諸性質に及ぼす影響についてみると，不充分な練和は低，高銅型を問わず断面状アロイの性質に著しい悪影響を及ぼすが，球状アロイにはその影響が比較的小さかったと考えられる。製造者の指示よりも過剰に練和した場合は機械的性質は若干向上するが，著しい発熱，操作時間の短縮，固化時の収縮を伴うので臨床的に利点があると思われなかった。物理的諸性質のうちで練和時間の影響を特に著明に表わしたのは，クリープであった。

CuPd-AuCu 銅 2 元合金の規則化過程と時効硬化機構

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CuPd-AuCu 銅 2 元合金の規則化と時効硬化機構を検討した。c/a 値（伝導電子濃度）が 0.87 以下と小さい合金では時効初期に短範囲規則化が進行し，その後不均一規則化機構により長範囲規則化が結晶粒界から起こった。これらの合金の時効硬化は CuPd 相または AuCu I 相の体積率の増加によるものであった。一方，c/a 値が