Microstructural Observations of Laser-Sintered Specimens
for Prosthodontic Applications

Thesis

Presented in Partial Fulfillment of the Requirements for the Degree of Master of Science
in the Graduate School of The Ohio State University

By
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Graduate Program in Dentistry

The Ohio State University
2013

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ABSTRACT

Objectives: Laser sintering is a recently introduced technology that has been used to prepare dental restorations from a biocompatible Co-Cr base metal alloy. The objectives of this study were to obtain detailed information about dimensional accuracy available with laser sintering, along with the microstructure and Vickers hardness of the alloy.

Methods: Representative maxillary coping and implant framework specimens were prepared from STL files by a commercial laser sintering apparatus (Phenix Systems), using the dedicated Co-Cr alloy. Compatible dental porcelain was bonded to the coping specimen (North Shore Dental Labs, Lynn, MA). Specimens were sectioned with a slow-speed diamond saw, prepared for metallographic examination by resin-mounting and polishing with a series of abrasives, and observed with a scanning electron microscope and optical microscope at a range of magnifications. Alloy compositions were obtained by x-ray energy-dispersive spectrometric analyses. A Co-Cr alloy implant framework prepared by conventional milling/polishing and a cast Ni-Cr alloy coping for a conventional metal-ceramic restoration with the dental porcelain served as controls. Microstructures of the laser-sintered and cast alloys were revealed by electrolytic etching. Values of Vickers hardness for the Co-Cr alloy in the laser-sintered implant framework and the coping for the metal-ceramic restoration were compared, along with the cast
coping. Dimensions of the milled/polished and laser-sintered implant frameworks were measured microscopically and compared.

**Results:** The laser-sintered Co-Cr alloy had a fine-grained microstructure, and there was some difficulty in revealing full details by electrolytic etching, whereas the cast Ni-Cr alloy had a well-defined dendritic microstructure. The laser-sintered Co-Co alloy coping had intimate interfacial attachment to dental porcelain. The Vickers hardness was slightly (< 10%, but statistically significant), higher for the laser-sintered Co-Cr implant framework, compared to the laser-sintered Co-Cr coping. The laser-sintered Co-Cr alloy was twice as hard as the cast Ni-Cr alloy. Fits on the original cast/die of the implant frameworks and metal-ceramic specimens were judged to be clinically acceptable by two prosthodontists. Dimensions of the laser-sintered and milled/polished implant frameworks were in excellent agreement for well-defined measurement locations.

**Conclusions:** The fine-grained laser-sintered Co-Cr alloy should have high values of strength, indicated by the high measured Vickers hardness. More research is needed for the electrolytic etching process to reveal the laser-sintered microstructure in greater detail. Use of a nanoindenter is recommended to provide further information about any local hardness variations in the microstructure. The laser-sintering process produces representative prostheses with clinically acceptable accuracy, in agreement with previous publications from other research groups.
ACKNOWLEDGMENTS

I would like to dedicate this thesis to my parents, and to my wife (Amal Ali-M Brkha, and my kids (Reda, Sanad, and Mohab Abolkair Fathalah), as well to my brothers and my sister for their care, love, support and encouragement.

I would like express my sincere gratitude to Professor William A. Brantley for sharing his knowledge and skill for my research with me during this study, and particularly his help in the preparation of this thesis. I appreciate the support, direction and guidance of Dr. Yonghoon Jeong, especially his help in the laboratory phase of this work in the Department of Materials Science and Engineering. I am most appreciative of Professors William Clark, William Johnston and Stephen Rosenstiel for their willingness to serve on my Master of Science thesis committee.

My special thanks are extended to Dr. Carl Drago for providing the dental prostheses for this investigation. I am grateful to Steven Bright for his guidance, interest, and particularly the substantial help in his laboratory in the Department of Materials Science and Engineering, and for the use of his camera which he so generously placed at my disposal. Also I would like to great thanks to Carl Kipp for his kind help in his laboratory in the College of Dentistry at Ohio State University and to Connie Mason for her quiet support and valuable help. Lastly, I would like to express my special thanks and gratitude to Professor Abu-Bakr Omar, Osama Omer, and Mohamed Hellal (Ephraim, Turkey) for their continued help and support.
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FIELDS OF STUDY

Major Field: Dentistry

Specialty: Dental Materials
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CHAPTER 1
INTRODUCTION

Current dental laboratory technology for preparation of all-metal restorations, and metal-ceramic prostheses generally employs procedures that were developed many decades in the past.\textsuperscript{1-3} All-metal restorations and metal copings for metal-ceramic restorations are cast using a labor-intensive lost-wax dental laboratory process with precision investments. Casting of the often-selected inexpensive base metal alloys is difficult because of their high melting range, which may require the use of induction melting, and potential for excessive oxidation. The Co-Cr metal alloys are more biocompatible than the Ni-Cr alloys because some patients have nickel allergy. Other advantages of the Ni-Cr and Co-Cr base metal dental casting alloys are their high strength and high modulus of elasticity. However, a disadvantage is that the high hardness of many of these base metal alloys, sometimes exceeding that of tooth structure, requires substantial time in the dental laboratory for finishing the castings. Recent research has shown that different melting and casting techniques used in the dental laboratory with Ni-Cr and Co-Cr alloys significantly influenced the ultimate tensile strength and percentage elongation, and it was emphasized that the dental laboratory should select the appropriate casting protocol for each alloy composition.\textsuperscript{4}
Currently, there is much research activity on the development of alternative processes that utilize modern technology to fabricate dental restorations more quickly at lower cost. One approach that has received attention recently is the use of laser sintering to prepare all-metal restorations, metal-ceramic restorations and removable partial dentures. Three European companies (Phenix Systems, Riom, France; Bego Dental, Bremen, Germany; EOS Dental, Munich, Germany) currently market commercial laser sintering apparatus that can be utilized to fabricate dental restorations. For example, the large and expensive Phenix PXM Dental System is claimed to be capable of producing 200 fixed restorations in 5 hours; 100 fixed restorations, 3 lower removable partial denture frameworks, and 3 upper removable partial denture frameworks in 9 hours; and 6 lower removable partial denture frameworks and 6 upper removable partial denture frameworks in 10 hours. This rate of production is vastly faster than is possible at large dental laboratories.

The laser-sintering process is one example of additive manufacturing technology, also termed three-dimensional printing, direct digital manufacturing by the military, or CAD/CAM (computer-aided design/computer-aided manufacturing), that has become very popular for engineering mass production applications. In the laser-sintering process, CAD or STL (stereolithography) image files from the scanned part are employed with a high-powered laser to fuse particles layer-by-layer on the powder bed of an alloy and build up the part rapidly. The metallurgical processes that occur during joining of the powder particles are complex. While the current laser-sintering technology is advancing rapidly, it should be noted that the CAD/CAM process for dental applications was introduced over 20 years ago to prepare ceramic inlays and veneers.
In order to have clinical longevity, metal–ceramic prostheses must have an acceptable fit to the prepared tooth structure and adequate bond strength between the alloy and porcelain.\textsuperscript{1-3} Recent studies have shown that laser-sintered Co-Cr crown specimens have satisfactory internal fit on dies\textsuperscript{9} and that metal-ceramic bonding of dental porcelain to air-abraded disc specimens of the laser-sintered Co-Cr alloy was not significantly different from that to similar cast specimens of the Co-Cr alloy\textsuperscript{6}.

The present investigation focused on the metallurgical structure and Vickers hardness of laser-sintered Co-Cr dental restorations, because such information is presently limited. An implant framework and a metal-ceramic restoration in which dental porcelain was bonded to the laser-sintered alloy were selected as representative examples for investigation. Detailed studies of the metallurgical structure are important for understanding the mechanical properties and anticipated clinical performance of the laser-sintered dental restorations. Vickers hardness measurements are highly useful, since alloy hardness is predictive of both mechanical properties and ease of laboratory finishing. In addition, careful microscopic measurements of the dimensions were obtained for the laser-sintered Co-Cr implant framework and another framework that had been precision-milled from the same STL file in order to investigate whether there were notable differences in their dimensions that would have clinical importance.
The two specific aims of this study were as follows:

1. To examine the microstructures and Vickers hardness of representative laser-sintered restorations prepared from the dedicated Co-Cr alloy to gain fundamental insight into predicted mechanical properties and clinical performance.

2. To compare detailed dimensional measurements of a representative implant framework fabricated from laser-sintered and commercially milled alloys, using the same STL file.
CHAPTER 2

Materials and Methods

Two representative specimens for prosthodontics were prepared by laser sintering: implant framework and coping for a metal-ceramic restoration. Specimens were prepared from STL files by the Phenix Dental System (Riom, France) laser-sintering apparatus, using the dedicated Co-Cr alloy. Compatible dental porcelain (Reflex Imagine, Wieland Dental, Pforzheim, Germany) was bonded to the laser-sintered coping using conventional techniques and standard multiple ceramic layers (North Shore Dental Labs, Lynn, MA). A milled/polished Co-Cr alloy implant framework was also prepared (BIOMET 3i, Palm Beach Gardens, FL) from the same STL file as the laser-sintered implant framework, along with a metal-ceramic specimen using a cast Ni-Cr alloy.

Initially, the laser-sintered and milled/polished implant frameworks were placed on the original dental stone model (Figure 1), and the metal-ceramic specimens were placed on the original die. In all cases, the fits were judged as clinically acceptable by two prosthodontists. For quantitative comparisons, the dimensions of the laser-sintered and milled/polished implant frameworks were determined using a measuring microscope (Measurescope, Model MM-II, Nikon, Tokyo, Japan), with digital readout counters (SC-111 and 112, Nikon, Tokyo, Japan), as shown in Figure 2. Replicate measurements (N = 5)
were made by two observers at 12 different locations on the upper and lower surfaces of both the laser sintered and milled/polished implant frameworks, as shown in Figure 3.

After completion of dimensional measurements, the laser-sintered and milled/polished implant frameworks were sectioned with a slow-speed water-cooled diamond saw (Vari-Cut VC50, LECO), shown in Figure 4, to yield smaller specimens for optical microscope (GX 71, Olympus) and scanning electron microscope (SEM) (Quanta 200, FEI) examination (Figure 5). The cut specimens were mounted using thermosetting bakelite (Buehler) and a press machine (PR-25, LECO) shown in Figure 6. Similar procedures were employed to obtained resin-mounted cross-sectioned specimens from the metal-ceramic specimens having cast Ni-Cr and laser-sintered Co-Cr copings.

Mounted specimens were polished with a series of abrasives, finishing with 0.3 μm particles (Micro Diamond, LECO), electrolytically etched (ElectroMet 4, Buehler), and examined with the SEM to investigate details of the microstructures. After extensive attempts with immersion etching, using known etchants for base metal alloys, an electrolytic etching procedure reported by Morris et al was found to yield excellent results for the microstructure. The etchant composition was 140 mL HCl with 1 g CrO₃, and the etching conditions were 3 V for 10 s. Specimen compositions were obtained by energy-dispersive spectrometric analyses (EDS) (Oxford Instruments) with the SEM.
Figure 1. Laser sintered implant framework placed on dental stone model.
Figure 2. Measuring microscope.

Figure 3. Locations of 12 different measurements made on upper and lower surfaces of laser-sintered and milled/polished implant frameworks.
Figure 4. Diamond saw cutting apparatus.

Figure 5. Scanning electron microscope.
Vickers hardness measurements were made on the resin-mounted specimens (Figures 7, 8 and 9). A 200 g indenting load was used, with a dwell time of 20 s. Ten indentations, separated by at least 10 indentation widths, were placed on each specimen. A digital Vickers hardness testing machine (Micromet II, Buehler), shown in Figure 10, was used with × 400 magnification for placement of the indentations.

**Figure 6.** Mounting press.

**Figure 7.** Resin-mounted laser-sintered implant framework specimen.

**Figure 8.** Resin-mounted milled/polished implant framework specimen.
Figure 9. Resin-mounted laser sintered (left) and cast (right) metal-ceramic specimens.

Figure 10. Digital Vickers hardness testing machine.

A photograph of the digital microscope screen for a representative hardness measurement is shown in Figure 11. The lengths of the two diagonals (D1 and D2 in microns) for the indentation can be seen on the top line. The calculated Vickers hardness (HV) number is shown on the second line, and it can also be seen that a corresponding Brinell hardness (HRB) has not been defined. The indenting load of 200 g is indicated at the bottom left of the screen image. Values of Vickers hardness number are reported in the tables to follow, and these values can readily be converted\textsuperscript{12} to GPa units.
Figure 11. Screen image of representative indentation and Vickers hardness data.

Mean values and standard deviations were determined for all measurement data. Dimensions of the milled/polished and laser-sintered implant frameworks and values of Vickers hardness for the laser-sintered Co-Cr alloy in the laser-sintered implant framework and in the coping for the metal-ceramic crown were compared, as described in the next chapter.
CHAPTER 3

Results

Figures 12 – 18 present a variety of SEM images of the laser-sintered implant framework surfaces at different locations, using a range of magnifications. These images suggest that the sintering process involves localized melting rather than complete fusion of the Co-Cr base metal alloy. Defects in the laser-sintered surface are attributed to incomplete impingement of alloy particles in the original powder bed, along with the presence of impurity particles in the bed, which are apparent in many photomicrographs. Individual powder particles appear to be in the approximate 20 μm size range, which should result in a small grain size for the laser-sintered base metal alloy. An oriented pattern in the microstructure appears to exist at some locations, as shown in Figure 18.

Figure 12. Low-magnification SEM image of laser-sintered implant framework.
Figure 13. High-magnification SEM image of top outside surface of ring-shaped projection on laser-sintered implant framework.

Figure 14. High-magnification SEM image of middle portion of outside surface of ring-shaped projection on laser-sintered implant framework.
**Figure 15.** SEM images at two magnifications of surface inside ring-shaped projection on laser-sintered implant framework.

**Figure 16.** SEM images of lateral surface of ring-shaped projection on laser-sintered implant framework.
**Figure 17.** SEM image of region on laser-sintered implant framework outside surface adjacent to area of ring projection.

**Figure 18.** SEM image of region on opposite surface of implant framework, showing laser sintering pattern in microstructure.
Optical microscope images of the polished and etched surfaces are shown in Figures 19 – 24 at magnifications from ×100 to ×1000 for the laser-sintered and cast copings of the metal-ceramic specimens, and SEM images at ×500 magnification are presented in Figures 25 and 26. The laser-sintered microstructure for the Co-Cr alloy has a finer scale than that for the cast Ni-Cr alloy, which shows a dendritic structure even at the relatively low ×100 magnification. No dendritic structure is evident in the SEM image for the laser-sintered Co-Cr alloy in Figure 25. Extensive efforts with the present electrolytic etching conditions were unable to yield better resolution for the laser-sintered microstructure than that shown in Figure 25. EDS results showing the alloy compositions for the cast coping, laser-sintered coping, and laser-sintered implant framework are presented in Figures 27 – 29. It can be seen that the cast alloy has a Ni-Cr base metal alloy composition, whereas the laser-sintered alloy has the reported Co-Cr alloy composition.

Figure 19. Optical microscope image of microstructure of etched metal-ceramic specimen with laser sintered coping (×100 original magnification).
Figure 20. Optical microscope image of microstructure of etched metal-ceramic specimen with cast coping (×100 original magnification).

Figure 21. Optical microscope image of microstructure of etched metal-ceramic specimen with laser sintered coping (×200 original magnification).
Figure 22. Optical microscope image of microstructure of etched metal-ceramic specimen with cast coping (×200 original magnification).

Figure 23. Optical microscope image of microstructure of etched metal-ceramic specimen with laser sintered coping (×500 original magnification).
Figure 24. Optical microscope image of microstructure of etched metal-ceramic specimen with laser sintered coping (×1000 original magnification).

Figure 25. SEM image of etched microstructure of laser-sintered coping for metal-ceramic restoration (×500 magnification)
Figure 26. SEM image of etched microstructure of cast coping for metal-ceramic restoration (×500 magnification)

Figure 27. Elemental composition of cast coping from EDS analyses.

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt %</th>
<th>At %</th>
</tr>
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<tbody>
<tr>
<td>Mo L</td>
<td>10.67</td>
<td>6.61</td>
</tr>
<tr>
<td>Cr K</td>
<td>22.33</td>
<td>25.54</td>
</tr>
<tr>
<td>Ni K</td>
<td>67</td>
<td>67.85</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
</tr>
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</table>
**Figure 28.** Elemental composition of laser-sintered coping from EDS analyses.

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt %</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo L</td>
<td>6.58</td>
<td>3.98</td>
</tr>
<tr>
<td>Cr K</td>
<td>29.97</td>
<td>33.48</td>
</tr>
<tr>
<td>Co K</td>
<td>63.45</td>
<td>62.54</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
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</tbody>
</table>

**Figure 29.** Elemental composition of laser-sintered implant framework from EDS analyses.

<table>
<thead>
<tr>
<th>Element</th>
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<tr>
<td>C K</td>
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<tr>
<td>MoL</td>
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<tr>
<td>CrK</td>
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<tr>
<td>CoK</td>
<td>68.47</td>
<td>64.43</td>
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<tr>
<td>Total</td>
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Vickers hardness measurements for the laser-sintered Co-Cr alloy coping, cast Ni-Cr alloy coping, and laser-sintered implant framework are summarized in Figure 30, where it is evident that the Co-Cr alloy is much harder than the Ni-Cr alloy. A small difference (much less than 10%, but statistically significantly different [P < 0.05], using a t-test) was found for the mean hardness of the two laser-sintered specimens, suggesting a possible size effect on VHN.

Figure 30. Vickers hardness measurements for (a) laser-sintered Co-Cr coping, (b) cast Ni-Cr coping, and (c) laser-sintered Co-Cr implant framework. Values are mean ± SD.
Tables 1 and 2 show the measured dimensions obtained by two observers at the 12 locations for the two implant frameworks (milled/polished and laser-sintered). Five measurements were made at each location by each observer, with mean ± standard deviations for the repeated measurements in the second and third columns. The right column shows the difference in mean values at each of the 12 locations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Milled/polished (mm)</th>
<th>Laser-sintered (mm)</th>
<th>Difference (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.136 ± 0.088</td>
<td>41.031 ± 0.021</td>
<td>105</td>
</tr>
<tr>
<td>2</td>
<td>14.647 ± 0.054</td>
<td>14.572 ± 0.048</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>17.941 ± 0.049</td>
<td>17.921 ± 0.032</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>8.030 ± 0.032</td>
<td>8.108 ± 0.048</td>
<td>78</td>
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<tr>
<td>5</td>
<td>14.890 ± 0.055</td>
<td>14.787 ± 0.056</td>
<td>103</td>
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<tr>
<td>6</td>
<td>3.498 ± 0.095</td>
<td>3.667 ± 0.027</td>
<td>169</td>
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<tr>
<td>7</td>
<td>2.552 ± 0.117</td>
<td>2.580 ± 0.015</td>
<td>28</td>
</tr>
<tr>
<td>8</td>
<td>3.490 ± 0.019</td>
<td>3.666 ± 0.014</td>
<td>176</td>
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<tr>
<td>9</td>
<td>12.500 ± 0.017</td>
<td>12.475 ± 0.030</td>
<td>25</td>
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<tr>
<td>10</td>
<td>7.339 ± 0.031</td>
<td>7.320 ± 0.024</td>
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<tr>
<td>11</td>
<td>14.890 ± 0.042</td>
<td>14.894 ± 0.029</td>
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<tr>
<td>12</td>
<td>13.570 ± 0.024</td>
<td>13.552 ± 0.024</td>
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Table 1. Measurements by first observer for implant frameworks.
<table>
<thead>
<tr>
<th>Location</th>
<th>Milled/polished (mm)</th>
<th>Laser-sintered (mm)</th>
<th>Difference (μm)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>41.781 ± 0.183</td>
<td>41.016 ± 0.041</td>
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<tr>
<td>2</td>
<td>14.614 ± 0.019</td>
<td>14.517 ± 0.038</td>
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<tr>
<td>3</td>
<td>18.011 ± 0.013</td>
<td>17.779 ± 0.037</td>
<td>231</td>
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<tr>
<td>4</td>
<td>8.034 ± 0.028</td>
<td>8.068 ± 0.040</td>
<td>34</td>
</tr>
<tr>
<td>5</td>
<td>14.808 ± 0.036</td>
<td>14.865 ± 0.038</td>
<td>57</td>
</tr>
<tr>
<td>6</td>
<td>3.490 ± 0.025</td>
<td>3.612 ± 0.031</td>
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</tr>
<tr>
<td>7</td>
<td>2.712 ± 0.029</td>
<td>2.940 ± 0.023</td>
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<tr>
<td>8</td>
<td>3.313 ± 0.081</td>
<td>3.620 ± 0.026</td>
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<tr>
<td>9</td>
<td>12.411 ± 0.028</td>
<td>12.484 ± 0.041</td>
<td>74</td>
</tr>
<tr>
<td>10</td>
<td>7.281 ± 0.049</td>
<td>7.263 ± 0.070</td>
<td>18</td>
</tr>
<tr>
<td>11</td>
<td>14.939 ± 0.034</td>
<td>14.896 ± 0.032</td>
<td>43</td>
</tr>
<tr>
<td>12</td>
<td>13.523 ± 0.048</td>
<td>13.568 ± 0.026</td>
<td>45</td>
</tr>
</tbody>
</table>

**Table 2.** Measurements by second observer for implant frameworks.
Comparisons of the differences (right column) in Tables 1 and 2 reveal that the measured dimensions of the laser-sintered and milled/polished implant frameworks were less similar (differences more than 100 μm) at sites 1, 5, 6, and 8 for the first observer and at sites 1, 3, 6, 7 and 8 for the second observer. Referring to Figure 3, it follows that the locations corresponding to these sites were generally more difficult to define in the measuring microscope than the locations for the other sites. Accordingly, the greater measurement discrepancies for the laser-sintered and milled/polished frameworks at the above locations were considered to arise from the difficulty of precisely defining these positions, and it was judged that there was generally no clinically important difference in the dimensions of the laser-sintered and milled/polished implant frameworks. This was consistent with the same clinical judgments when the two implant frameworks were placed on the original dental stone model (Figure 2). A more definitive conclusion about the relative accuracy of laser-sintered and milled/polished implant frameworks prepared from the same STL files requires a larger sample size, and this is an important area for future research.
CHAPTER 4

Discussion

While the focus of this thesis investigation was the metallurgical structure of the laser-sintered Co-Cr alloy in two representative prostheses, initial attention was directed to the accuracy of these prostheses. The representative prostheses were judged in a clinical manner to have adequate fit, and this was confirmed by detailed measurements of the dimensions of the milled/polished and laser-sintered implant frameworks showing minimal differences in several dimensions on the implant frameworks where the measurement sites could be well defined. Previously, Ucar et al. found that there was no significant difference in the internal fit of laser-sintered and cast Co-Cr alloy crowns. It was consequently deemed unnecessary in the present study to make marginal discrepancy measurements on its dedicated die for the metal-ceramic specimen having a laser-sintered coping, since the handling involved might damage the metal-ceramic interfacial region.

Because the milling and polishing process for an implant framework requires considerable time by the implant company and preparation of a cast coping for a metal-ceramic restoration likewise requires substantial dental laboratory time, the preparation of prostheses by laser sintering is a considerable advance in dental technology, enabling much more rapid production at much lower cost.
An important dental materials science finding from this investigation was the special nature of the microstructure of the laser-sintered Co-Cr alloy. The polished and electrolytically etched microstructure was fine-scale (Figures 24 and 25), but greater detail would be desirable and further research to optimize the electrolytic etching process for the laser-sintered microstructure is needed. In recent work elsewhere using an electrolytic etchant that also contained HCl, Gurbuz et al.\textsuperscript{13} reported that the laser-sintered Co-Cr alloy had a honeycomb microstructure with a 1 μm (characteristic) length. Evidence of a finer-scale substructure is evident on close examination of Figure 25. A fine-scale microstructure would provide improved mechanical properties, compared to those for the cast Co-Cr alloy (not investigated in the present study), which should have a coarser microstructure with dendrites.\textsuperscript{4,14,15} It should be noted that the cast Ni-Cr alloy for the metal-ceramic specimen had a dendritic microstructure (Figures 20, 22, and 26) that were very similar to microstructures reported previously by Baran\textsuperscript{16} for cast Ni-Cr alloys. An interdendritic phase is particular evident in Figure 26 for the present cast Ni-Cr alloy.

An interesting observation was the slightly higher (< 10%) Vickers hardness for the laser-sintered coping for the metal-ceramic specimen, compared to the Vickers hardness for the laser-sintered implant framework. This difference in VHN should correspond to minimal difference in the clinically important yield strength of the two laser-sintered specimens.\textsuperscript{12} Whether there is a size effect on Vickers hardness and other mechanical properties of laser-sintered dental prostheses requires further study.

The interface had intimate contact between the laser-sintered Co-Cr alloy and the dental porcelain (Figures 19 and 20). This is consistent with the previous observation by Akova et al.\textsuperscript{6} that there was no significant difference in mean shear bond strength with
porcelain for the same Co-Cr alloy in the cast and laser-sintered conditions. A worthwhile future study would be a comparison of the microtensile bond strength for metal-ceramic specimens with cast Ni-Cr alloy and laser-sintered Co-Cr alloy copings.

While detailed information about the Co-Cr alloy powder particles used for the laser-sintering are proprietary with the manufacturer (Phenix Systems), SEM images (Figures 15 and 16) obtained in the present study suggest that the largest particles have diameters less than about 50 μm. As would be expected, these SEM images also suggest the presence of smaller-diameter particle, which would be needed to have a densely packed starting powder bed for the laser sintering. Other interesting microstructural observations in the present study were the presence of some porosity and extraneous fine particles in the microstructures of the laser-sintered alloy (Figures 13, 14, 17-19, 21, and 23-25), which may affect mechanical properties and clinical longevity of laser-sintered restorations and prostheses. A future study, perhaps including the use of a nanoindenter to measure more localized variations in hardness, will be needed to investigate this hypothesis. It is important to note that the highly textured nature of the laser-sintered surface provides microirregularities for adherence of dental porcelain in metal-ceramic restorations or the penetration of dental resin for clinical usage of a implant framework.

In closing, it is evident that many further studies of the applications of laser sintering for dentistry are needed. There is presently only limited understanding of the relationships between the laser operating conditions, the nature of the powder bed of alloy particles, and the resulting surface texture, microstructure, and properties of the base metal alloy restorations and prostheses. Laser sintering is a definite advance in dental technology for the 21st century and should be given high priority as an area of
future dental materials science research and laboratory technology development. At present no company in the United States is marketing laser sintering equipment for dental applications.
CHAPTER 5
CONCLUSIONS

Under the conditions of this study, the following conclusions can be drawn:

1. Laser sintering yields dimensions of prostheses that are similar to those for the same prostheses prepared by current slower dental laboratory techniques. Further research on laser-sintering for dental applications is urged.

2. The microstructure of the laser-sintered Co-Cr alloy has a characteristic fine-scale which should result in superior strength of the alloy.

3. Additional etching experiments should be performed on the laser-sintered Co-Cr alloy with the goal of obtaining improved microstructural details.

4. The intimate interfacial attachment observed between the laser-sintered Co-Cr alloy coping and the dental porcelain suggests good metal-ceramic bonding.

5. There is a small difference between the Vickers hardness of the laser-sintered implant framework and the coping for the metal-ceramic restoration. While this difference should be clinically important, further research is needed to determine whether a specimen size effect exists for properties of laser-sintered restorations and prostheses.

6. A nanoindenter may be useful in future research to investigate local variations of mechanical properties for laser-sintered restorations and prostheses.
REFERENCES


