Effect of Heat Treatment on Joint Properties of Laser-Welded Ag-Au-Cu-Pd and Co-Cr Alloys

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Purpose: This study investigated the effect of heat treatment on the strengths of laser-welded cast Ag-Au-Cu-Pd and Co-Cr alloys.

Materials and Methods: Cast plates of Ag-Au-Cu-Pd (Ag) and Co-Cr (Co) alloys were prepared. After polishing the surfaces to be welded, the plates were matched and butted Ag to Ag (Ag/Ag), Co to Co (Co/Co), and Ag to Co (Ag/Co) and welded using Nd:YAG laser at a pulse duration of 10 ms, spot diameter of 1 mm, and voltage of 200 V. Five specimens were prepared for each experimental condition by bilaterally welding them with five spots. The Ag/Ag, Ag/Co, and control Ag underwent two heat treatments—softening (ST) and hardening (AH). A group of as-cast specimens serving as controls was not given either heat treatment. The failure load and percent elongation were measured at a crosshead speed of 1.0 mm/min.

Results: The fracture resistance of Co/Co was similar to that of the control Co, while the fracture resistance of Co/Ag was significantly lower than that of both like alloy pairings for all heat-treating conditions. The control Ag had greater fracture resistance after AH and lower fracture resistance after ST. The AH treatment increased the fracture resistance, and the ST treatment decreased the fracture resistance of both Ag/Ag and Co/Ag, although not significantly. The percentage of elongation appeared to positively correlate with the fracture resistance results.

Conclusions: The results obtained in this study indicated that the age-hardening heat treatment increased the weld strength between the paired Au-Ag-Cu-Pd alloys and between the Au-Ag-Cu-Pd and Co-Cr alloys.

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INDEX WORDS: laser, mechanical properties, Ag-Au-Cu-Pd alloy, Co-Cr alloy, welding

COBALT-CHROMIUM (Co-Cr) alloys are commonly used to fabricate cast metal frameworks for removable partial dentures; however, clasps and connectors made of Co-Cr often fatigue and fracture from repeated insertion/withdrawal movements and masticatory loading.[1-3] Preexisting internal porosities induced by the casting procedure can also cause metal frameworks to break.[4,5] Broken frameworks may be repaired by connecting broken pieces, or in the case of a lost piece, by fabricating that piece with a similar or different alloy and connecting it to the framework. Laser welding is especially useful for repairing broken partial dentures since this technique minimizes the heating of the metal outside the welding spot,[6] thus preserving any acrylic resin already affixed to the framework. Laser welding is especially useful on base metal alloys such as Co-Cr since they have lower thermal conductivities and higher rates of laser beam absorption compared with gold alloys.[7,8] In general, the greater the rate of laser beam absorption and the lower the thermal conductivity, the greater the penetration of the laser into each metal.[7]

When gold alloys are laser welded to Co-Cr alloys, however, the joint strength may be reduced. This reduction may result in part from the difference in laser penetration between the two alloys. The laser penetration into gold alloys is normally less, compared with the Co-Cr alloy, due to the higher thermal conductivity and lower rate of laser beam absorption of gold. Connecting different

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alloys such as Co-Cr and gold also reduces the joint strengths, because of the different mechanical properties of each alloy, as is commonly observed when soldering a stiff parent alloy using a weak solder.[9]

To compensate for the differences in alloy properties, dental casting gold alloys can be heat treated to modify their mechanical properties, yielding a softer or harder alloy.[10] Heat treatments are usually accomplished using manufacturer-recommended procedures. Our previous studies indicated that heat treating the metal after laser welding improved the mechanical strength of the gold alloy joints.[11] Heat treatments administered after laser welding may also strengthen the joints between gold and Co-Cr alloys.

The purpose of this study was to use tensile testing to evaluate the effect of heat treatments on the joint strengths of an Ag-Au-Cu-Pd alloy laser welded to a Co-Cr alloy.

Materials and Methods

Preparation of Cast Plates

The two casting alloys used in this study were Ag-Au-Cu-Pd alloy (Ag: 51%, Au: 12%, Cu: 14.5%, Pd: 20%, other: 2.5%; New Gold Para, Ishifuku Corp., Tokyo, Japan) and Co-Cr alloy (Co: 60.6%, Cr: 31.5%, Mo: 6%, others: 1.9%; Vitallium, Austenal, Chicago, IL). Wax plate patterns were prepared for the laser welded (0.5 × 3.0 × 10 mm) and nonwelded (control) (0.5 × 3.0 × 20 mm) specimens. The wax patterns were invested in the molds and then cast with each metal. The Ag-Au-Cu-Pd alloy (hereafter designated "Ag") was cast conventionally using a broken arm centrifugal casting unit (Kerr Centrifico, Kerr Manufacturing Corp., Romulus, MI) and a cristobalite investment (Cristobalite, Whip Mix Corp., Louisville, KY). The Co-Cr alloy (hereafter designated "Co") was also cast conventionally using an induction melting centrifugal casting machine (Modular 4, CMP Industries Inc., Albany, NY) and a phosphate investment (V.R. Investment, Austenal). Each casting procedure followed the manufacturer's instructions. After casting, the molds were bench cooled to room temperature. The cast plates were then divested, air-abraded with 50 μm Al_2O_3 particles, and ultrasonically cleaned with acetone for 10 minutes.

Preparation of Laser-Welded Specimens

After the 3.0 × 0.5 mm surfaces of the two plates (0.5 × 3.0 × 10 mm) were polished with No. 600 SiC paper, they were butted against one another using a jig. The plates were matched and butted Ag to Ag (designated "Ag/Ag"), Co to Co ("Co/Co"), and Co to Ag ("Co/Ag"). The assembled cast plates were then welded with Nd:YAG laser (Neolaser L, Girrbach Dental Systems, Pforzheim, Germany) at a constant voltage of 200 V, pulse duration of 10 ms, and spot diameter of 1 mm. The laser-welding conditions were determined by correlating the penetration depth of the laser into each metal as measured in a previous study[12] with the thickness of the specimens used in this study. The laser was perpendicularly applied to the interface of two plates. For each experimental condition, five specimens were prepared. Each specimen was bilaterally welded with five laser spots per side (Fig 1). First, three laser spots (1 mm spot diameter) were linearly applied to cover the 3-mm width on one side, and two laser spots were added to overlap with 50% of the three previously applied spots. The same procedure was then performed on the other side.

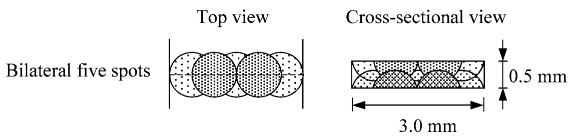

Figure 1. Laser-welding configurations used.

Heat Treatment

Sets of Ag/Ag, Co/Ag, and Ag control specimens were heat treated according to the manufacturers' instructions for the Ag alloy. Two heat treatments were administered: solution heat treatment [750°C for 20 min, then quenched in ice water ("ST")] or age-hardening treatment [350°C for 30 min, then bench cooled ("AH")]. As-cast ("AC") specimens were reserved without being heat treated.

Tensile Testing

Tensile testing was conducted with a universal testing machine (Model 1125, Instron Corp., Canton, MA) at a crosshead speed of 1 mm/min and a gauge length of 10 mm. Grips were attached 5 mm from both ends. Failure load (N) and elongation (%) were recorded, and the means ($n = 5$) and standard deviations were calculated. The data were statistically analyzed using an ANOVA (Tukey's Honest Significant Difference Test) and Student's t-test at a significance level of $\alpha = 0.05$. After tensile testing, the fractured surfaces were examined using scanning electron microscopy (JSM-6300, JEOL, Peabody, MA).

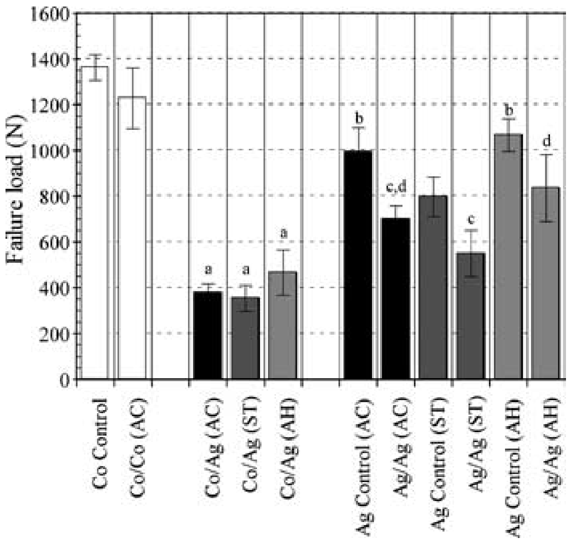

Figure 2. Failure load (N) of the specimens. Identical letters indicate no significant differences ($p > 0.05$) in each pairing or among heat treatments.

Results

The results of failure load to fracture and elongation are presented in Figures 2 and 3, respectively. The fracture resistance of Co/Co was similar to that of the control Co (Fig 2). The Co/Ag proved to be significantly weaker than both like alloy pairings for all three heat-treating conditions. The control Ag had high fracture resistance for AH and low fracture resistance for ST. The fracture resistance improved after the AH treatment and deteriorated after the ST treatment in both Ag/Ag and Co/Ag, although there were no significant differences ($p > 0.05$). The percentage of elongation appeared to positively correlate with the fracture resistance results; however, the elongation was similar among the heat treatments for the Ag/Ag and Co/Ag groups as well as the control group.

Figure 4 displays the entire fracture surface of each of the laser-welded Ag/Ag (Fig 4A), Co/Ag (Fig 4B), and Co/Co (Fig 4C) specimens. The cross sections of all the Co/Ag specimens indicated that they were not completely welded, whereas the Ag/Ag and Co/Co specimens were entirely welded. There were many pores in the fracture surfaces of the Ag/Ag (Fig 4A). Figure 5 shows the micrographs of the fracture surfaces. The control Co (Fig 5A) underwent dendritic fracture that is commonly observed in the fracture surface of Co-Cr alloys,[8] whereas the laser-welded Co/Co (Fig 5B) fractured in a brittle manner with cleavage fracture having acicular river patterns. The fracture surfaces of the three heat-treating conditions were similar (Fig 5C vs. 5D; Fig 5G vs. 5H) for Ag/Ag and Ag/Co. The Ag/Ag and Ag/Co fracture surfaces were different in that the Ag/Ag surface was finely dimpled while the Co/Ag surface was more planar. Control Ag (Figs 5E and 5F) had a

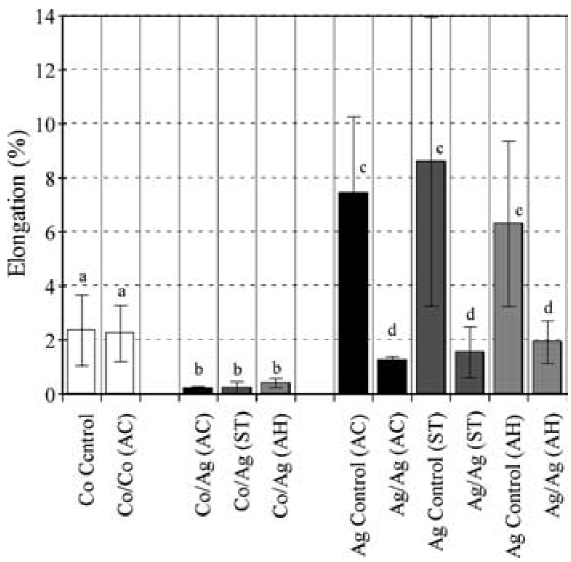

Figure 3. Elongation (%) of the specimens. Identical letters indicate no significant differences ($p > 0.05$) in each pairing or among heat treatments.

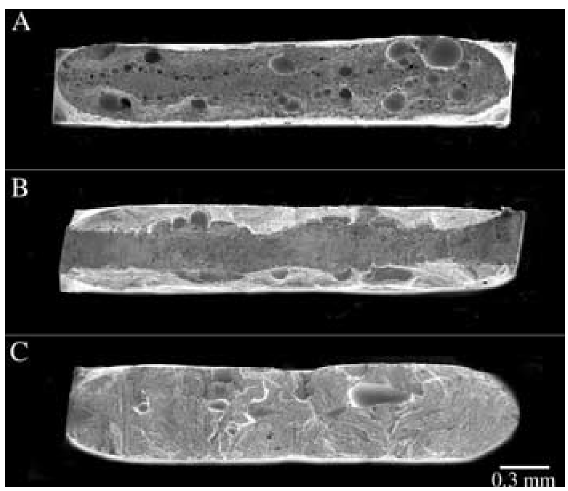

Figure 4. SEM photographs of entire fracture surfaces of the specimens. (*A*) Ag/Ag (Laser). (*B*) Co/Ag (Laser). (*C*) Co/Co (Laser).

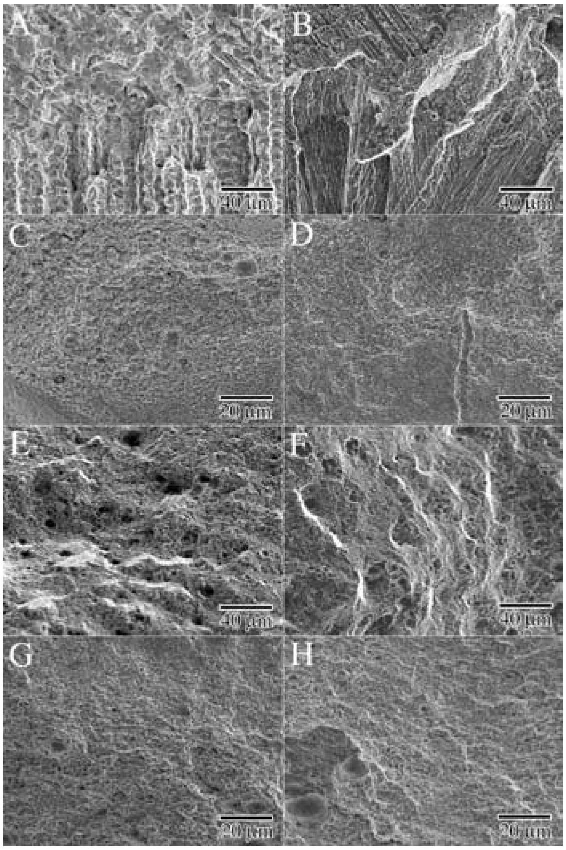

Figure 5. SEM micrographs of fracture surfaces of the specimens. (*A*) Co (Control). (*B*) Co/Co (Laser). (*C*) Co/Ag (Laser; AC). (*D*) Co/Ag (Laser; AH). (*E*) Ag (Control; ST). (*F*) Ag (Control; AH). (*G*) Ag/Ag (Laser; ST). (*H*) Ag/Ag (Laser; AH).

rougher fracture surface compared with the laser-welded Co/Ag and Ag/Ag groups.

Discussion

The weld strength of laser-welded Co/Co was similar to that of the control Co (Fig 2), whereas the strength of the laser-welded Ag/Ag did not reach that of the nonwelded control specimens. Note that the failure loads of the heat-treated Ag/Ag groups decreased 20% to 30% after laser welding. The difference between the Co and Ag groups may be attributed to the porosity created during the laser-welding process. The number of pores observed in the fracture surfaces of the laser-welded Ag/Ag was much higher than in the Co/Co (Figs 4A and 4C). The failure loads for the Co/Ag were significantly less than for both homogeneous alloy pairings (Ag/Ag at all heat treatment conditions and Co/Co). The welds of all Co/Ag specimens were incomplete, as shown in cross section (Fig 4B), whereas the Co/Co specimens were entirely welded (Fig 4C); the Ag/Ag specimens retained a small area that was unwelded (Fig 4A). It can be assumed that the difference in the quality of the welding area contributed greatly to the lower weld strength of Co/Ag. When the Ag and Co were laser welded, the metals comprising the Ag and Co alloys were alloyed in the weld zone. The welding of two dissimilar alloys (Ag/Co) may necessitate a higher energy compared with the welding of like alloys (Ag/Ag and Co/Co). Because the same amount of laser energy was applied to weld these combinations under the same welding parameters (voltage, pulse duration, and spot diameter), the laser beam penetrated the Ag/Co less at the interface, resulting in an incomplete weld, as indicated by the cross-sectional fracture surfaces (Fig 4B). Therefore, the joint strength of the Ag/Co can be improved by increasing the laser energy (and thus penetration) used for welding.

A comparison of the fracture surfaces of Ag/Co, control Ag, and Ag/Ag (Figs 5C–G) shows that the control Ag had a rougher fracture surface compared with the laser-welded Co/Ag and Ag/Ag groups. The Ag/Ag and Ag/Co fracture surfaces differed in that Ag/Ag was finely dimpled while Co/Ag was more planar. The visible roughness of the fracture surfaces fell in the order of control Ag > Ag/Ag > Co/Ag, which corresponds to the order of elongation values (Ag > Ag/Ag > Co/Ag). These results suggested that the rougher the fracture surface, the more the specimens elongated, and greater the fracture resistance of the Ag containing specimens.

Clinically, the results obtained in the present study indicate that if Ag and Co alloy prosthetic frameworks are to be laser welded, the welding conditions that produce high laser energy should be chosen to achieve deeper laser penetration at the interface and thus, higher joint strength. Furthermore, age-hardening heat treatment is recommended to produce stronger welded joints. More investigation will be necessary to understand adequate laser penetration into the interface between Co-Cr and Ag-Au-Cu-Pd alloys before these findings can be clinically applied. These procedures may allow effective repair and salvage of existing removable prostheses.

Conclusion

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

1. The fracture resistance of the laser-welded Au-Ag-Cu-Pd and Co-Cr alloys was lower than that of both like alloy pairings due to incomplete welding at the interface.
2. The results indicated that the age-hardening heat treatment increased the weld strength of Au-Ag-Cu-Pd alloy, and the weld strength between Au-Ag-Cu-Pd and Co-Cr alloys.

Acknowledgments

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