Mechanical properties of experimental dental Au-Ag-Cu alloys after heat treatments

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Abstract

Objective: The purpose of this study was to determine the mechanical properties of three experimental dental Au-Ag-Cu alloys consisting of 30-50% Au, 30-50% Ag, and 20% Cu after softening and hardening heat treatments.

Materials and methods: Twelve specimens were prepared from three Au-Ag-Cu alloys (50%Au-30%Ag-20%Cu, 40%Au-40%Ag-20%Cu, and 30%Au-50%Ag-20%Cu alloys) and divided into two groups (softening and hardening), all specimens were loaded until fracture occurred using a universal testing machine. Tensile strength, 0.2% proof stress, elastic modulus, and elongation were determined from load-extension curves. The data of mechanical properties were statistically analyzed using One-way ANOVA followed by multiple comparison tests at 95% confidence interval.

Results: No significant differences were found in the elastic modulus between softening and hardening for each experimental alloy, and among the three alloys for each heat treatment ($p>0.05$). The tensile strength and 0.2% proof stress of the hardening groups were significantly higher than those of the softening groups, while the hardening groups had significantly lower elongation than the softening groups ($p<0.05$). The tensile strength of 30Au-50Ag-20Cu alloy was significantly lower than those of the other alloys ($p<0.05$), and no significant differences were found in the tensile strength between 50Au-30Ag-20Cu and 40Au-40Ag-20Cu alloys ($p>0.05$) after softening heat treatment. For the hardening, the tensile strength and 0.2% proof stress of 30Au-50Ag-20Cu alloy were significantly lower than those of the other alloys ($p<0.05$), and no significant differences were found in the tensile strength and 0.2% proof stress between 50Au-30Ag-20Cu and 40Au-40Ag-20Cu alloys ($p>0.05$). No significant differences were found in elongation among the three alloys ($p>0.05$).

Conclusion: The mechanical properties of the three Au-Ag-Cu alloys (50%Au-30%Ag-20%Cu, 40%Au-40%Ag-20%Cu, and 30%Au-50%Ag-20%Cu alloys) could be modified by heat treatments. According to ISO 22674: 2006, and based on the evaluated mechanical properties, all three experimental alloys can be recommended as suitable alloy for crown & bridges and inlays.

Key words: dental Au-Ag-Cu alloys, elastic modulus, elongation, heat treatments, mechanical properties, tensile strength

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Introduction

Dental casting gold alloy has been widely used to fabricate dental restorations such as inlays and crown & bridges for many years because of its ease of cast characteristics, excellent properties, and high detail reproduction. Dental casting gold alloy is easy to cast because of its low melting range, where a gypsum-bonded investment can be used to prepare the casting mold. It can also be melted using a gas-air torch to cast into the mold using a centrifugal casting machine.[1] This casting procedure is easy and convenient, which is an important consideration for the dental laboratory technician.[2] Most of the dental casting gold alloys contain a ternary system of gold, silver, and copper with possibly zinc or other metals in small quantities, and it can be divided into two groups, the high-gold content alloy (at least 70%) and the low-gold content alloy (approximately 50%).[1]

Nowadays, alternative low-gold alloys have been developed instead of the high-gold alloys due to the high price of gold; however the properties of alternative low-gold alloys must be suitable for use. The mechanical properties as required by the ISO 22674: 2006,[3] are divided into six types for fixed and removable applications. The mechanical properties of the basic Au-Ag-Cu ternary alloys can be changed by heat treatments if there are appropriate compositions.[4] In general, heat treatments of dental casting alloys are divided into two types: softening and hardening heat treatments.

The purpose of this study was to determine the mechanical properties of three experimental Au-Ag-Cu alloys (50%Au-30%Ag-20%Cu, 40%Au-40%Ag-20%Cu, and 30%Au-50%Ag-20%Cu alloys) after softening and hardening heat treatments, and to explore suitable Au-Ag-Cu alloys for dental applications.

Materials and Methods

Alloy preparation

Three experimental Au-Ag-Cu alloys (50Au-30Ag-20Cu, 40Au-40Ag-20Cu, and 30Au-50Ag-20Cu) were prepared in a silica tube (inside diameter: 20 mm) under argon gas atmosphere using an induction melting unit (High Frequency Induction Heating Unit – 10 kW SCR, Tokyo Koshuha-Denkiro Co. Ltd., Tokyo, Japan).

Specimen preparation

Twelve tensile test specimens were prepared from each of the three experimental Au-Ag-Cu alloys. Each tensile test specimen (diameter: 2 mm, gauge length: 20 mm) was prepared using an ordinary dental casting procedure. A gypsum-bonded investment (Cristobalite micro, GC Corporation, Tokyo, Japan) was used to prepare the casting mold. Each experimental Au-Ag-Cu alloy was melted using a gas-air torch and cast into the mold using a centrifugal casting machine (Caster VC500, The Daiei Dental MFG. Co. Ltd., Osaka, Japan). Molds were bench-cooled to room temperature before specimens were taken from the mold, and surfaces of specimens were cleaned using an ultrasonic cleaner. All specimens were softened by heating at 700°C for 10 minutes in a furnace (KDF D90, Denken, Kyoto, Japan), and then quenched immediately in ice water. Six specimens were reserved for testing at the softening heat treatment. The remaining six specimens were subject to the hardening heat treatment, which were further heated at 450°C and left in a furnace to cool down to 250°C taking 35 minutes, and then specimens were quenched in ice water.

Measurement and data analysis

Tensile strength, 0.2% proof stress, elastic modulus, and elongation were measured using a universal testing machine (Shimazu Autograph DSS5000, Shimazu Seisakusho, Kyoto, Japan) equipped with an extensometer (Extensometer SG10-50, Shimazu Seisakusho, Kyoto, Japan) at a cross-head speed of 2 mm/min. A load-extension curve was recorded on a chart for each specimen. Tensile strength, 0.2% proof stress, elastic modulus, and elongation were determined from the recorded chart. The data of elastic modulus and elongation were statistically analyzed using One-way ANOVA and Tukey's multiple comparison test at 95% confidence interval, while the data of tensile strength and 0.2% proof stress were statistically analyzed using One-way ANOVA and Dunnett's T3 test comparison test at 95% confidence interval.

Results

The mean values and standard deviations for tensile strength, 0.2% proof stress, elastic modulus, and elongation, as well as the statistical differences between the mean values are shown in Table 1.

Tensile strength

Tensile strength of the experimental alloys ranged from 389.2 to 463.5 MPa for the softening heat treatment, and 583.8 to 709.3 MPa for the hardening heat treatment. The highest was 50Au-30Ag-20Cu alloy followed by 40Au-40Ag-20Cu alloy, and 30Au-50Ag-20Cu alloy. The tensile strength of 30Au-50Ag-20Cu alloy was significantly lower than those of the other experimental alloys ($p<0.05$), while no significant difference was found in tensile strength between 50Au-30Ag-20Cu alloy and 40Au-40Ag-20Cu alloy ($p>0.05$). Tensile strength of the softening heat treatment was significantly lower than those of the hardening heat treatment for all experimental alloys ($p<0.05$).

0.2% proof stress

0.2% proof stress of the experimental alloys ranged from 247.7 to 417.5 MPa for the softening heat treatment, and 536.2 to 700.5 MPa for the hardening heat treatment. The highest was 50Au-30Ag-20Cu alloy, followed by 40Au-40Ag-20Cu alloy, and 30Au-50Ag-20Cu alloy. The results from analysis showed that 30Au-50Ag-20Cu alloy had significantly lower 0.2% proof stress than the other experimental alloys for both the softening and hardening heat treatments ($p<0.05$). 50Au-30Ag-20Cu alloy had significantly higher 0.2% proof stress than 40Au-40Ag-20Cu alloy for the softening heat treatment ($p<0.05$), while no significant difference was found in 0.2% proof stress between 50Au-30Ag-20Cu alloy and 40Au-40Ag-20Cu alloy for the hardening heat treatment ($p>0.05$). For all experimental alloys, 0.2% proof stress of the softening heat treatment was significantly lower than those of the hardening heat treatment ($p<0.05$).

Table 1 Tensile strength, 0.2% proof stress, elastic modulus, elongation, and comparison between means

Alloy	Heat treatment	Tensile strength (MPa)	0.2% proof stress (MPa)	Elastic modulus (GPa)	Elongation (%)
50Au-30Ag-20Cu	Softening	463.5(11.1) b	417.5(8.3) g	85.67(4.18) j,k	12.05(3.73) m
	Hardening	709.3(30.7) d	700.5(27.9) i	90.17(3.37) k	2.25(0.95) l
40Au-40Ag-20Cu	Softening	452.5(4.7) b	336.0(4.8) f	83.83(3.76) j,k	21.25(1.31) n
	Hardening	682.0(33.3) d	653.2(35.2) i	89.33(3.72) j,k	2.43(1.33) l
30Au-50Ag-20Cu	Softening	389.2(10.1) a	247.7(7.7) e	82.83(6.31) j	28.32(2.07) o
	Hardening	583.8(19.0) c	536.2(25.8) h	86.33(1.86) j,k	4.73(1.87) l

Standard deviations in parentheses

Average values with the same letters at the right-side of the standard deviation are not significantly different at $p>0.05$.

Elastic modulus

Elastic modulus of the experimental alloys ranged from 82.83 to 85.67 GPa for the softening heat treatment, and 86.33 to 90.17 GPa for the hardening heat treatment. The highest was 50Au-30Ag-20Cu alloy followed by 40Au-40Ag-20Cu alloy, and 30Au-50Ag-20Cu alloy. No significant differences were found in elastic modulus among all three experimental alloys for each heat treatment, and no significant differences were also found in elastic modulus between the softening and hardening heat treatments for each experimental alloy ($p>0.05$).

Elongation

Elongation of the experimental alloys ranged from 12.05 to 28.32 % for the softening heat treatment, and 2.25 to 4.73 % for the hardening heat treatment. No significant differences were found in elongation among all three experimental alloys for the hardening heat treatment ($p>0.05$). On the other hand, significant differences in elongation among all the three experimental were found in the softening heat treatment wherein the highest was 30Au-50Ag-20Cu alloy followed by 40Au-40Ag-20Cu alloy, and the lowest was 50Au-30Ag-20Cu alloy ($p<0.05$). For all the experimental alloys, elongation of the softening heat treatment was significantly higher than those of the hardening heat treatment ($p<0.05$).

Discussion

The present study investigated the mechanical properties of three experimental Au-Ag-Cu alloys (50%Au-30%Ag-20%Cu, 40%Au-40%Ag-20%Cu, and 30%Au-50%Ag-20%Cu alloys) after softening and hardening heat treatments, and explored suitable Au-Ag-Cu alloys for dental applications. The mechanical properties of the basic Au-Ag-Cu ternary alloys can be changed by heat treatments if there are appropriate compositions. In general, heat treatments of dental casting alloys are divided into two types: softening and hardening heat treatments.

The result of this study showed that the mechanical properties of three experimental Au-Ag-Cu alloys can be changed by heat treatments. The increase in the strength and the decrease in elongation with the hardening heat treatment may be explained by phase transformation from Cu-rich (α_2, Cu-Au) phase in the softened Au-Ag-Cu alloys to $AuCu_3$-ordered phase in the hardened Au-Ag-Cu alloys as shown in Figure 1 and Figure 2. The temperatures used in this study were set at 700°C for softening heat treatment and 450 → 250°C for hardening heat treatment.[5] Figure 1 shows the Au-Ag-Cu isothermal section at 700°C, which indicates that all the softened experimental alloys may consist of Ag-rich (α_1, Ag-Au) and Cu-rich (α_2, Cu-Au) phases.[6] For the hardening heat treatment, the temperature (450 → 250°C) used in this study was close to the temperature (300°C) in Figure 2, which indicated that all the hardened experimental alloys might consist of Ag-rich and $AuCu_3$-ordered phases.[7] It has been reported in literatures[4,8,9] that the formation of $AuCu_3$-ordered phase is responsible for the hardening of AuCu alloy system, and the $AuCu_3$-ordered phase is also responsible for the increase in the strength. As Au content decreased from 50% to 30% with Ag content increased from 30% to 50%, decrease in strength and increase in elongation for softened experimental alloys might be caused by the Cu-rich phase decreased (Figure 1). The Cu-rich phase is rather harder than the Ag-rich phase.[10] While strength decreased for the hardened experimental alloys might be caused by decrease of $AuCu_3$-ordered phase (Figure 2). Further studies including X-ray diffraction analysis and detailed microstructural observation are necessary to explore the hardening mechanism of the Au-Ag-Cu alloy to clarify the formation of phases.

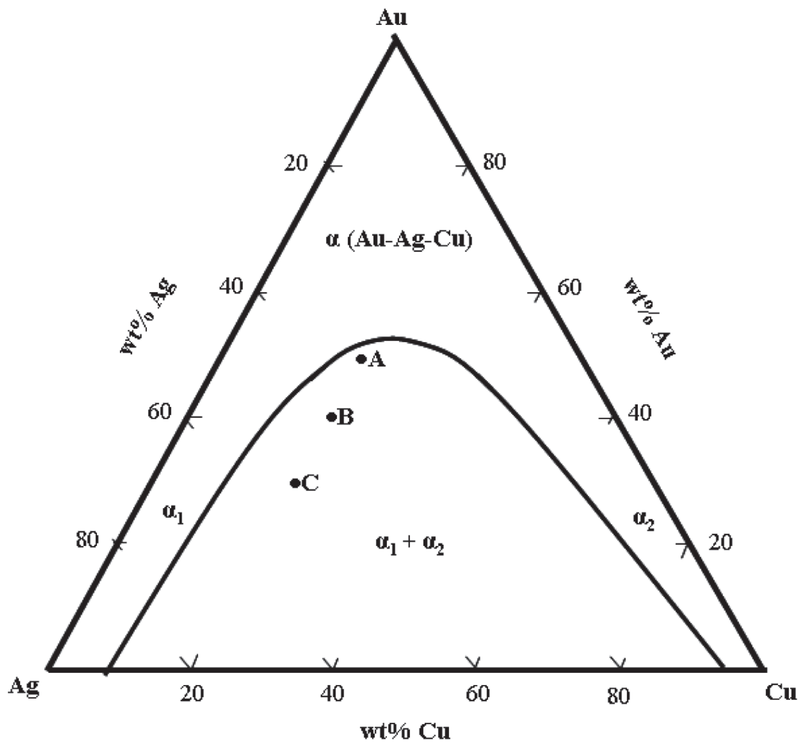

Figure 1 Au-Ag-Cu isothermal section at 700°C (A: 50Au-30Ag-20Cu alloy, B: 40Au-40Ag-20Cu alloy, and C: 30Au-50Ag-20Cu alloy)[6]

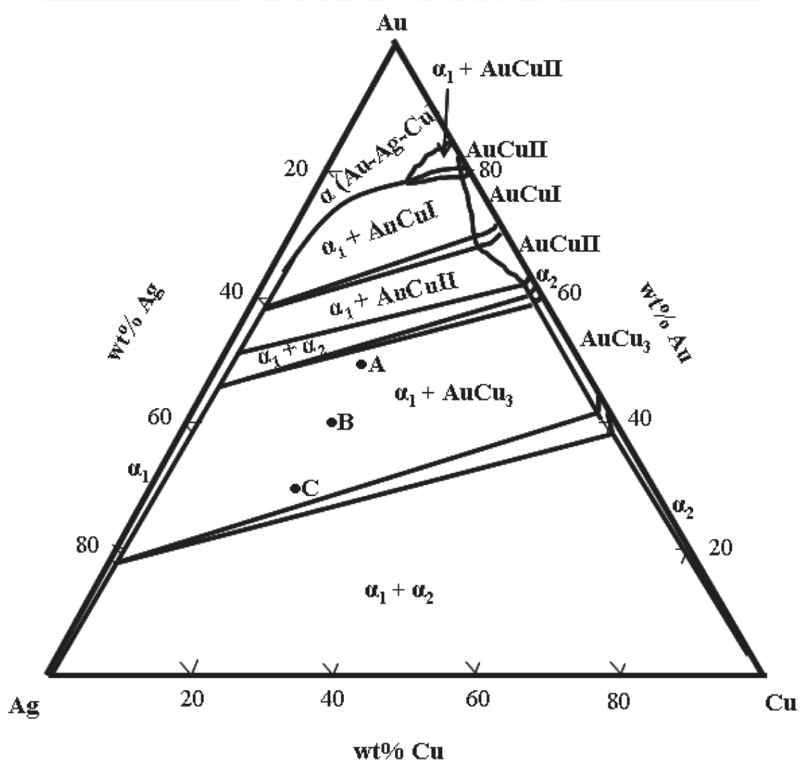

Figure 2 Au-Ag-Cu isothermal section at 300°C (A: 50Au-30Ag-20Cu alloy, B: 40Au-40Ag-20Cu alloy, and C: 30Au-50Ag-20Cu alloy)[7]

Mechanical properties are important properties for dental restorations, which are required by the ISO 22674: 2006, and mechanical properties are divided into six types for fixed and removable applications as shown in Table 2. The result of this study shows that the mechanical properties of all the three experimental alloys (Table 1) passed the ISO 22674: 2006 for use in Type 2-4 (Table 2). Moreover, the mechanical properties of 40Au-30Ag-20Cu and 30Au-50Ag-20Cu alloys (Table 1) also met the standards in ISO 22674: 2006 for use in Type 1(Table 2).

The mechanical properties of all experimental alloys passed ISO 22674: 2006 requirements for Type 2-4 (Table 2), tensile strength was not the requirement in this standard. However, the result of this study showed that the tensile strength of all experimental alloys (Table1) was lower than the commercial product (40Au-Ag-Cu alloy: soft 586 MPa and hard 890 MPa).[11] Therefore, these alloys should be developed by adding some elements such as indium in small quantities because indium is used as a strengthener and hardener in both gold and palladium alloys,[12] and it has been demonstrated by Churnjitapirom et al[13] that the strength of 35Ag-30Pd-20Au-15Cu alloy increased as indium content increased from 0% to 2% for the softening heat treatment and the hardening heat treatment at 400°C.

In conclusion, the result of this study shows that the mechanical properties of three Au-Ag-Cu alloys (50%Au-30%Ag-20%Cu, 40%Au-40%Ag-20%Cu, and 30%Au-50%Ag-20%Cu alloys) can be changed by heat treatments. According to ISO 22674: 2006, and based on the evaluated mechanical properties, all three experimental alloys can be recommended for dental restorations such as crown & bridges and inlays.

Table 2 ISO 22674: 2006 classification for fixed and removable applications, and their mechanical properties[3]

Type	0.2% proof stress (MPa) minimum	Elongation (%) minimum	Elastic modulus (GPa) minimum
0	-	-	-
1	80	18	-
2	180	10	-
3	270	5	-
4	360	2	-
5	500	2	150

Type 0: intended for small veneered one-surface inlays, veneered crowns.
Type 1: intended for veneered or unveneered one-surface inlays, veneered crowns.
Type 2: intended for crowns of inlays without restriction on the number of surface.
Type 3: intended for bridges (multiple unit fixed)
Type 4: intended for appliances with thin sections such as removable partial dentures, clasps, thin veneered crowns, wide-span bridges or bridges with small cross-sections, bars, attachments, implant retained superstructures.
Type 5: intended for appliances in which parts required the combination of high stiffness and strength such as thin removable partial dentures, parts with thin cross-sections, clasps.

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