THE COPPER-NICKEL ALLOY SYSTEM FOR DENTAL APPLICATIONS MECHANICAL PROPERTIES

M.F. Khalil, BDS, MScD, PhD;* H.Mohammed Al-Tahawai, DDS, MScD, PhD;**
Chiayi Shen, BS, MSc, PhD***

في هذا البحث تمت دراسة أربعة سبائك وذلك بهدف تقويم سبيكة غير نبيلة تتبع نظام سبائك النيكل والنحاس .

تركز جزء من الدراسة على تقييم الخصائص الميكانيكية لهذه السبائك مثل قوة احتمال الشد ، درجة الصلابة . ولقد دلت نتائج هذه الدراسة بأن قيم الخواص الميكانيكية لجميع السبائك الأربعة ما عدا سبيكة رقم ٤ تقع ما بين خصائص السبائك الذهبية والسبائك غير النبيلة .

Four types of alloys were investigated to determine the feasibility of developing a non-noble casting alloy based on the copper-nickel system. Emphasis was given to the evaluation of its mechanical properties, which included tensile properties and hardness. Tensile properties included yield strength, ultimate tensile strength, modulus of elasticity and ductility.

As demonstrated in this study, the four alloys, with the exception of alloy 4, possessed mechanical properties of intermediate values between those of gold and base-metal alloys.

Introduction

In spite of not being tooth-colored, metals have received wide application in dentistry, especially in restorative dentistry. The reason behind their success is that they generally possess high yield strength, reasonable amount of ductility and toughness. Furthermore, metals can be highly polished and generally maintain a lustrous and smooth surface for long periods of time, which is essential for a good periodontal health.

Gold and its alloys have been used in restorative dentistry since the early 1900's. Recently, a number of alloys with lower gold content have been introduced to the dental profession to render the same services to the patient but at a lower cost. Alloys containing non-noble metals were also developed and marketed for casting restorations. The major clinical disadvantages of the latter alloys are their inherent high value of surface hardness and yield strength, and lack of adequate ductility. These properties combined made finishing, polishing, and burnishing of conventional base-metal alloys rather difficult. Moreover, the high melting range of these alloys necessitates the use of special types of investment materials and high temperature casting methods.

Through the use of improved strengthening mechanisms, a number of non-noble cobalt-chromium and nickel-chromium alloys have been developed and used as substitutes for dental gold alloys.[1-6] This new generation of base-metal alloys, designed specifically for casting restorations, possess levels of ductility and yield strength comparable to those of Types III and IV gold alloys; yet, hardness and melting range continued to be higher.

The purpose of this series of studies was to investigate the feasibility of developing a non-noble dental casting alloy based on the copper-nickel system in an attempt to alleviate some or all of the above problems.

Literature review showed that certain metal alloy systems that have not yet been investigated could be potentially useful for developing a new dental alloy. Among these systems is the copper-nickel system modified by other elements to improve its strength and corrosion resistance. Chromium was found to be the most important element to impart corrosion resistance to nickel and iron-based alloys.[7-10] Aluminum on the other hand contributes

---

*Formerly Assistant Professor of Dental Materials

** Professor & Head of Division of Dental Materials, Department of Prosthetic Dental Sciences, King Saud University, College of Dentistry, P.O.Box 60169, Riyadh 11545, Saudi Arabia

*** University of Florida, Gainnesville, Fl, USA

Address reprint requests to: Dr. M. Khali to the strength and corrosion resistance of both copper and nickel alloys.[11-12] With some metallurgical consideration in mind, a group of alloys were developed and presented in a previous study.[13] The alloy group was composed of 75 different alloy compositions. These alloys were subjected to a preliminary corrosion study[14] which yielded four compositions that are resistant to corrosion in both distilled water and artificial saliva.

The present study was conducted in order to evaluate the mechanical properties of these four alloys.

Nickel-copper alloys that contain more than 50% nickel benefit from two features: by the high degree nobility of copper, and by the ability of nickel to protect itself through the formation of a passive oxide film.[15] Such alloys are generally more resistant to corrosion under both reducing and oxidizing conditions than nickel alone. Nickel-copper alloys also show good corrosion resistance to all common organic acids. These alloys are also virtually free from corrosion by natural and alkaline compounds, fruits, and other food acids. The addition of other elements, such as chromium and molybdenum, to nickel-copper alloys, improves their resistance to corrosion even further.[15] Data obtained from several sources[7,8,16,17] showed that the mechanical properties of nickel-copper alloys are somewhere between those of dental gold alloys and dental base-metal alloys. While gold alloys possess a yield strength (YS) of 179 MN/m^2 and an ultimate tensile strength (UTS) of 255 MN/m^2, conventional base-metal alloys have the values of 512-699 MN/m^2 and 720-1092 MN/m^2, respectively. Nickel-copper alloys on the other hand possess a YS value of 241 MN/m^2 and UTS value of 517 MN/m^2. The surface hardness of the three types of alloys also follows the same pattern. The Brinell Hardness Number (BHN) of gold, nickel-copper, and conventional base-metal alloys is 105, 150 and 240, respectively. The presence of aluminum in nickel-chromium alloys increased their yield strength and ultimate tensile strength considerably through the formation of a precipitate of nickel and aluminum with the composition Ni_3Al. Quantitative analysis of certain base metal dental alloys[16] revealed the presence of aluminum as an alloying element at a concentration ranging from 0.2% to 3.8%.

Materials and Methods

The four alloys (designated 1, 2, 3, and 4), which proved to be resistant to corrosion in a previous study,[14] were subjected to mechanical testing. The composition of these alloys is presented in Table 1.

The mechanical characteristics that were evaluated included tensile properties and hardness. Tensile properties included yield strength, ultimate tensile strength, modulus of elasticity and ductility. Ductility was determined as percent elongation and percent reduction in cross sectional area.

Tensile Properties Determination:

Five tensile bars were prepared from each alloy composition. The specimens were cast using the lost wax method. The investment material used was sulfate bonded investment* which is normally used in dental gold alloy casting.

Tensile test specimen [Fig. 1] was 35 mm long and 2.5 mm in diameter as recommended by the American Dental Association.[18]

The tensile test was performed using a universal testing machine.** A 25 mm strain gauge extensometer was calibrated and attached to the sample during testing. To obtain accurate calculation of the modulus of elasticity, a magnification of one thousand was used for the first 1 % elongation. The cross head speed used was 0.5 mm/minute and the chart speed was 50 mm/minute. Therefore, this setting allowed for elongation magnification of one hundred, after the first 1 % elongation have been determined by the extensometer.

After completing each tensile test, the cross section of each sample at the fracture site was precisely measured. The ductility as a function of reduction in cross sectional area was determined using the formula.

$$\text{\% reduction in cross section area} = \frac{A_0 - A_1 \times 100}{A_0}$$

Table 1. Chemical composition of alloys used for mechanical testing.

%	1	2	3	4
Cu	39.22	48.39	39.68	43.48
Ni	39.22	32.36	39.68	43.48
Al	3.92	4.84	2.78	2.17
Cr	17.65	14.52	17.86	10.81

---

* Cristobalite Sybron Corporation, Kerr Dental Division, Romlus, Michigan, USA

** Instron Universal Testing Machine, Intron Inc., Canton, Mass, USA

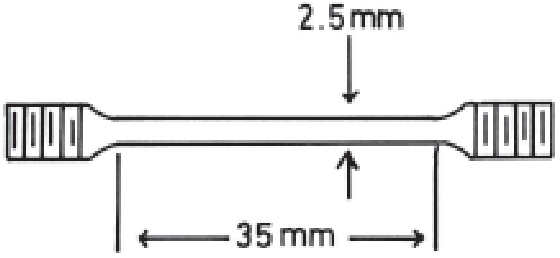

Fig. 1. Tensile test specimen.

Surface Hardness Determination:

The hardness of the specimens as a function of surface resistance to indentation was determined using a Rockwell hardness tester.* The B scale which is 100 kg. load and 1/16" ball was used. Rectangular cast specimens 20 mm x 10 mm x 5 mm were used.

After casting, each specimen was cleaned and the surface was ground to 400 grit. Five measurements, at least 2 mm apart, were obtained from each sample. The mean of the five readings on each specimen was reported as its average. Using a conversion chart, all values were converted to Brinell hardness numbers. The data for each hardness test were obtained from five samples of each alloy composition.

The mean, standard deviation, standard error and the 95% confidence interval for each mechanical property were calculated. Analysis of variance (ANOVA) was used to determine significant differences, if any, among the means of each property for the four alloys.

The mechanical properties of the alloys under investigation were compared to those of type III dental gold alloys and to those of base-metal alloys. Since beryllium-containing base metal alloys vary significantly from those that are beryllium-free in their mechanical properties, the values of the two groups were reported separately.

Results

The mean values of the 0.2% offset yield strength, UTS, elastic modulus, percent elongation, percent reduction in cross sectional areas, and hardness together with the 95% confidence limits for each alloy are given in Figures 2-7, respectively.

Yield Strength:

The mean value for alloy 2 was 377 MN/m^2 which was the highest among the four alloys. Alloy 1 had a slightly lower value of 334 MN/m^2. Alloys 3 and 4 had the lowest values of 296 and 271 MN/m^2, respectively. There was no significant difference in the yield strength of the latter two alloys.

In general the yield strength of the four alloys had intermediate values between those of gold alloys (179 MN/m^2) and conventional base-metal alloys (512-669 MN/m^2).

Ultimate Tensile Strength:

The ultimate tensile strength of the first three alloys ranged from 478 MN/m^2 to 445 MN/m^2 with no significant difference among the means. Alloy 4 possessed a UTS value of 306 MN/m^2 which was significantly lower than any of the three. The ultimate tensile strength values of the four alloys were higher than that of gold alloys (255 MN/m^2) but lower than those of base-metal alloys especially the beryllium-containing ones.

Modulus of Elasticity:

The modulus of elasticity of the four alloys ranged from 145 x 10^3 MN/m^2 for alioy 4 to 120 x

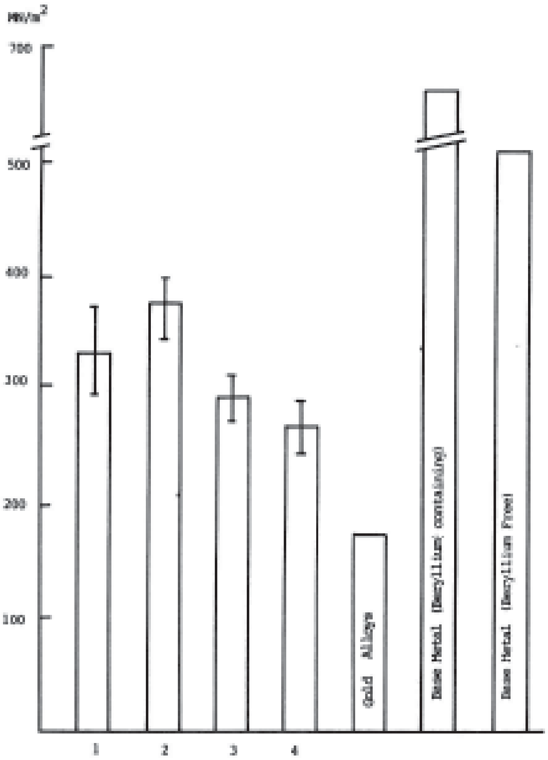

Fig. 2. Yield strength (MN/m^2)

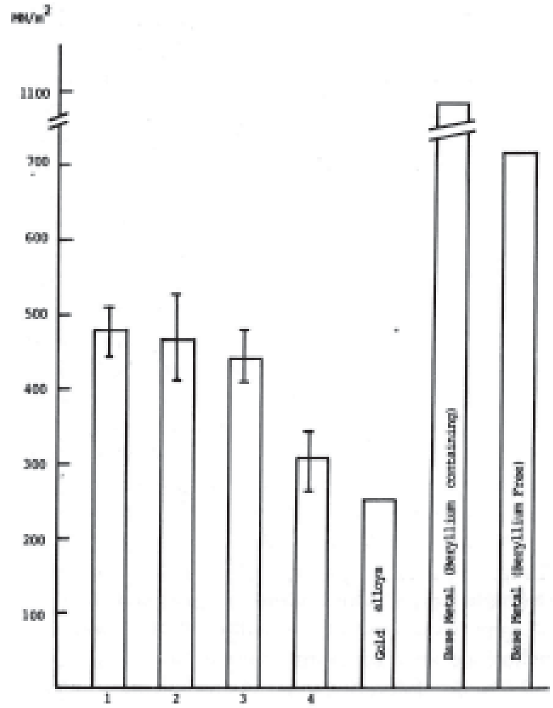

Fig. 3. Ultimate tensile strength (MN/m²)

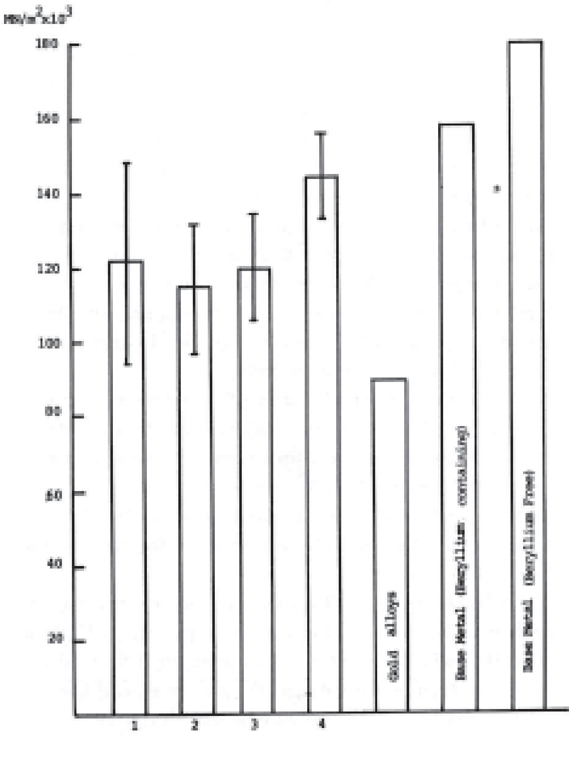

Fig. 4. Modulus of elasticity (MN/m² x 10^{1})

10^3 MN/m² for alloy 3. Analysis of variance revealed no significant differences among the means of the four alloys.

As with the previously mentioned properties, the modulus of elasticity values obtained for the experimental alloys were intermediate between those of gold and base-metal alloys.

Ductility:

As a function of percent elongation, the highest mean ductility value obtained was 22.1 % for alloy 3. This value was comparable to that of gold alloys (22.5%). Alloys 1 and 2 possessed values of 14.6% and 15.4% respectively which were not significantly different from each other. The values for alloys 1 and 2 were almost equivalent to those of the beryllium-free base-metal alloys. However, beryllium-containing base-metal alloys possessed a mean value of 18.4% which was significantly higher than those of alloys 1 and 2. Alloy 4 showed very limited ductility (< 2.0%).

As a function of the reduction in cross sectional area, the mean ductility values for alloys 1,2 and 3 were 19.9%, 21.5%, and 21.2%, respectively. These three values were practically comparable to that of gold alloys which is 22.2%. The values were higher than those for base metal alloys by approximately 2 to 3 percent. Alloy 4 showed much lower ductility relative to the first three alloys with a value of 5.5%.

Hardness:

The mean values for alloys 1,2, and 3 were between that of gold alloys (BHN 140) and that of base-metal alloys (BHN 224-256). Alloy 1 possessed a hardness number of BHN 153 which is close to that of gold alloys. Alloys 2 and 3 showed hardness values of BHN 202 and 206 which are much higher than that of the gold alloys, yet still lower than those for base-metal alloys especially the beryllium-containing ones. The hardness of alloy 4, similar to its yield strength and UTS, was the lowest among all alloys.

Discussion

In general, the mechanical properties of the four alloys tested possessed values between those of gold alloys and base metal alloys. The only exception was alloy 4 which showed very low ductility.

The yield strength of a given alloy determines its resistance to permanent deformation. It is impor-

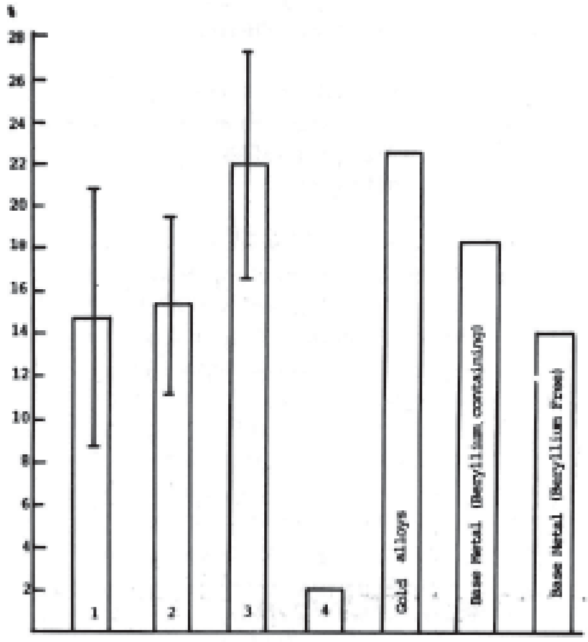

Fig. 5. Ductility (% elongation)

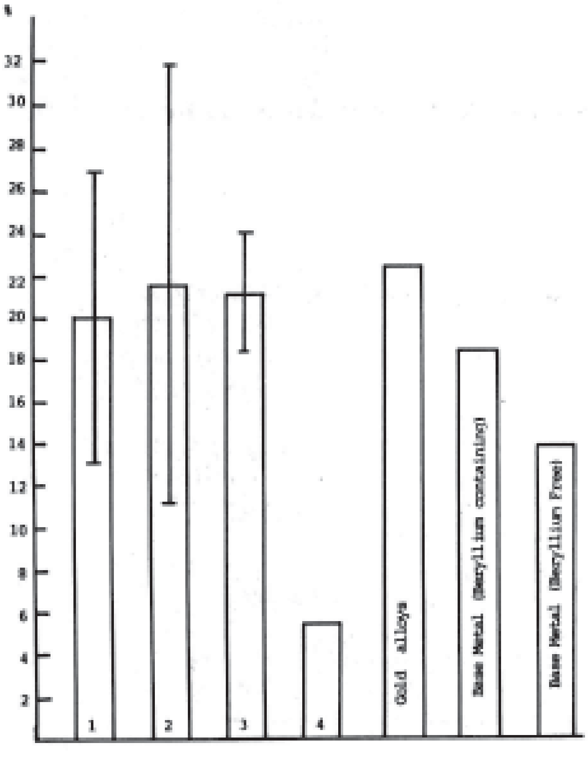

Fig. 6. Ductility (% reduction area)

tant that dental restorations do not deform plastically under masticatory stress. Large restorations, such as long span bridges, are more likely to deform if made of alloys with low yield strength. Therefore, the alloys under investigation appeared to be more advantageous than gold alloy in this respect. Yet, a reasonable yield strength that permits burnishing is also necessary. The experimental alloys seem to fulfill that criteria as well.

The differences in yield strength among the four alloys tested may be related to their aluminum concentrations. Such a relationship is depicted in Figure 8. Alloy 2 which contained the highest aluminum concentration (4.84 wt.%) possessed a yield strength of 377 MN/m^2 which was also the highest among the four alloys. Alloy 4 which contained the lowest percentage of aluminum {2.17 wt.%) possessed a yield strength of 271 MN/m^2 which was the lowest value among the alloys. Alloys 1 and 2 possessed intermediate yield strength values which were proportional to their aluminum concentrations. Although the maximum difference in aluminum concentration was only 2.77%, the difference in yield strength was 63 MN/m^2. This observation emphasized the importance of aluminum as a strengthening element in nickel and copper containing alloys. As previously mentioned, aluminum strengthens copper-nickel alloys through solid solutions and by the precipitation of the intermetallic compound Ni_3Al.

Although the ultimate tensile strength is an important parameter in characterizing the mechanical properties of any alloy system, it has little clinical significance in restorative dentistry. The reason for such insignificance is that once a dental restoration is permanently deformed, it will not serve its functions and will have to be replaced. In other words, in dentistry, once the yield strength is exceeded, the restoration fails.

The ultimate tensile strength of the first three alloys (1, 2, and 3) showed no significant differences. Alloy 4 on the other hand possessed a significantly lower ultimate tensile strength. The latter alloy contained the lowest concentration of aluminum which was believed to be the reason for the lack of strength.

Each of the four alloys possessed a significantly higher modulus of elasticity compared to that of dental gold alloys. This result indicated that alloys of this system are more rigid than dental gold alloys. The importance of the elastic modulus of alloys used in restorative dentistry are illustrated at least in

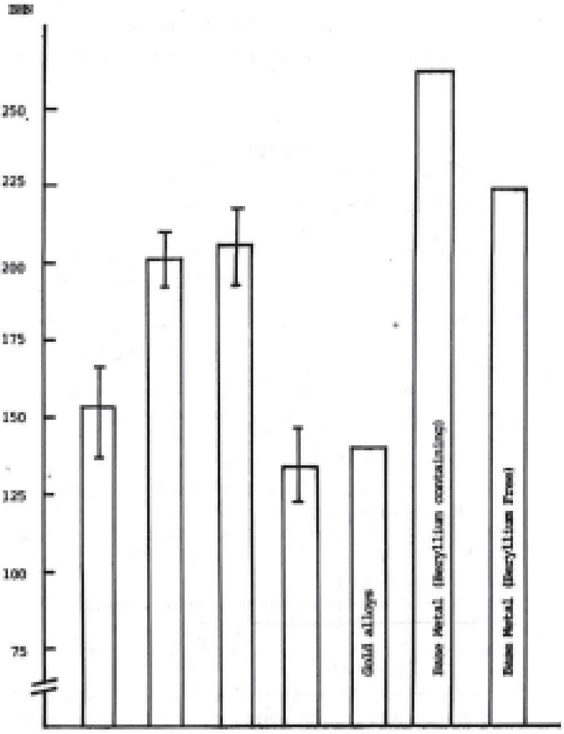

Fig. 7. Brinell Hardness Number

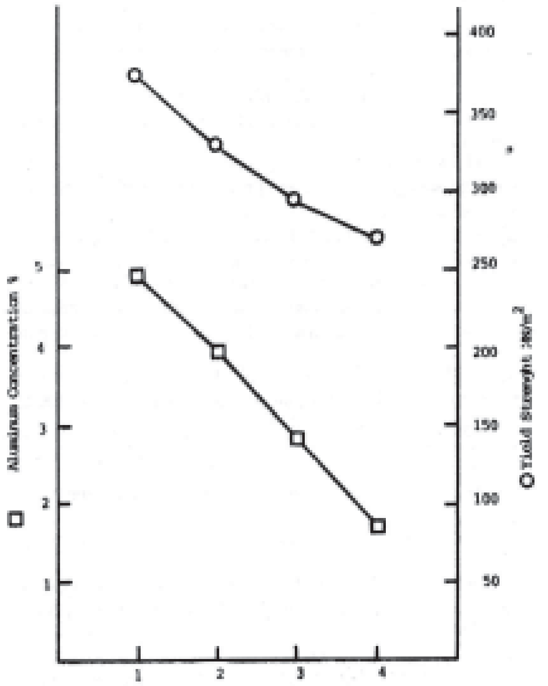

Fig. 8. Correlation between the yield strength and the aluminum concentration.

two situations. Firstly, long span bridges have a tendency to deform elastically under the masticatory stress especially when made of alloys of lower elastic moduli. As the bridge deforms, it also becomes shorter in a mesiodistal direction causing slight tilting of the abutment teeth towards the edentulous space. The frequent occurrence of this "flexing" phenomenon leads eventually to loosening of the supporting teeth with possible breakdown of the cementing material holding the retainers to the abutment teeth. Secondly, in ceramo-meta! restorations the porcelain veneer has a very limited ability to accommodate elastic deformation. If the metal substrate is not rigid enough, elastic deformation is likely to occur. Since the porcelain is baked directly on the surface of the metal substrate, fracture of porcelain occurs with metal deformation. Therefore, the modulus of elasticity of gold-palladium-silver and gold-palladium alloys used for ceramo-metal restorations[19] ranges from 117 x 10^3 to 124 x 10^3 MN/m^2(17x 10^6 –18 x 10^6psi). Alloy 4 showed a modulus of elasticity of 145.4 x 10^3 MN/m^2 (21 x 10^6 psi) which appears to be higher than that of the first three alloys. However, analysis of variance showed no significant difference in the mean values of the modulus of elasticity among the four alloys tested. The elastic modulus is only slightly influenced by small additions of the alloying elements.[20] Since there is only little difference in composition among the four alloys, the difference in the modulus of elasticity was not significant. The higher modulus of elasticity of the experimental alloys, relative to that of gold alloys, seemsto offer clinical advantage.

The ductility in terms of percent elongation showed mean values of 14.7%, 15.5%, and 22.2% for alloys 1, 2, and 3, respectively. This range is considered adequate with respect to dental applications. On the other hand, alloy 4 showed very limited elongation which was less than 2%. As mentioned previously, the same alloy (4) showed lower values of yield strength and ultimate tensile strength. The lack of strength of alloy 4 was believed to be due to the lower concentration of aluminum and possibly that of chromium. The lack of ductility is more related to the microstructure which will be discussed in a subsequent study of this series of articles.

The total deformation in tensile testing consists of two components, a uniform extension up to necking, then localized extension after necking. An appreciable amount of deformation is concentrated at the neck region. The smaller the gauge length is, the greater the contribution from the neck to the elongation and the higher is the ductility.[21] This observation emphasizes the importance of the ratio between the gauge length of the tensile specimen and its cross sectional area. In the United States, the ASTM standard length/diameter ratio (L/D) for a tensile specimen is four. The British and German (L/D) ratio is five and ten, respectively.

In the present study, the L/D ratio of the tensile specimen recommended by the American Dental Association was approximately 14. With this relatively high L/D ratio, the values obtained as percent elongation were considered lower than they would have been if the L/D ratio was lower. To eliminate this discrepancy in the results, the percent reduction in cross sectional area was calculated and the ductility was determined therefrom.

In terms of reduction in cross sectional area alloys 1, 2, and 3 showed a ductility of 19.9%, 21.5%, and 21.2%, respectively. Compared to the previously obtained values in terms of percent elongation, alloys 1 and 2 showed a gain in ductility of 5 to 6%. Alloy 4 showed slightly higher value (5.5%), yet still too low relative to that required for dental alloys.

The hardness of the four alloys were generally lower than that of base-meta! dental alloys. Alloys 1,2, and 3 showed higher values than that of gold alloys while alloy 4 showed a slightly lower hardness number. The best alloy among the first three alloys was alloy 1 which has a BHN of 153. This value is very close to that of gold alloys (145), which made alloy 1 rather easy to finish and polish. Although alloys 2 and 3 possessed higher BHN values (206 and 201 respectively), they were not as hard to finish as current base-metal alloys. This behavior is also due to their moduli of elasticity which are lower than that of base-metal alloys.

Conclusion

1. Alloys of the copper-nickel system are potentially suitable for dental applications provided that they contain adequate chromium concentration for corrosion protection.
2. Aluminum is an effective strengthening element in copper-nickel alloys.
3. Alloys 1,2, and 3 in this study possess mechanical properties of intermediate values between those of dental gold alloys and base metal alloys.
4. Alloy 1 is believed to be the best among the four alloys for its relatively lower surface hardness.

References

1. Mohammed H*, Asgar K. A new dental superalloy system: I. Theory and alloy design. J Dent Res 1973:52(1):136-44.
2. Mohammed H*, Asgar K. A new dental superalloy system: II. Mechanical properties. J Dent Res 1973;52(1):145-50.
3. Mohammed H*, Asgar K. Bigefcw WC. A new dental superalloy system: III. Micrestructure and phase transformations. J Dent Res 1973;52(l):151-6.
4. Mohammed H*, Asgar K, Kimball O.F. A new dental superalloy system: IV. X-ray diffraction analysis. J Dent Res 197;3:52(41:744-9.
5. Mohammed H*, Asgar K. A new dental superalloy system: V. Embrittling phase transformations. J Dent Res 1974;53(1):7-14.
6. Mohammed H, Abdullah SI, Mumford C. A new dental superalloy system: VI. Heat treatment. J Dent Res 1974;53(2): 379-84.
7. Phillips RW. Skinner's science of dental materials. 8th ed. Philadelphia: WB Saunders Co, 1982
8. Craig RG, Peyton FA, Restorative dental materials. 5th ed. St. Louis: CV Mosby Co, 1975.
9. ASM Committe on Corrosion of Stainless Steel: The selection of stainless steel of atmospheric and marine corrosion crevice. Metal Handbook, Vol 1, ASM, Metal Park, Ohio, 1967.
10. Park RM. Bens FP, Chromium base alloys, ASTM Symposium and Materials for Gas Turbine Engines, ASTM, Philadelphia, Pa, 1964.
11. Henderson D, Steffel V, MaCracken's partial denture constructions, principles and technique. 3rd ed. St. Louis: CV Mosby Co, 1969.
12. Brown RH, Binger WW. The resistance of aluminum alloys to corrosion. Metal Handbook, Vol 1, ASM, Metals Park, Ohio, 1967.
13. Khalil MF, Mohammed H", Shen C. Potential of Cu-Ni-Al-Cr as a dental alloy system. J Dent Res 1981 ;60(A)(Spec tss), AbstNo. 521.
14. Khalil MF, Tahawi HM*, Hassaballa M. The properties of copper-nickel alloys as dental alloy system. Part I. Preliminary corrosion study. Alexandria Dent J 1988:1 3(31:9-31.
15. Friend WZ. The resistance of nickel and nickel alloys to corrosion. Metal Handbook, 8th ed. Vol I ASM, Metals Park, Ohio, 1967.
16. Moffa JP. Physical and mechanical properties of gold and base metal alloys. Alternative to gold alloys in dentistry. NIH, Bethesda, Maryland, 1977
17. Everhart JL, Engineering properties of nickel and nickel alloys. New York: Plenum Press, 1971
18. Guide to denta! materials and devices, 8th ed. Chicago:ADA, 1976-1978,
19. Hansen M. Constitution of binary alloys. 2nd ed. New York: McGraw-Hill Book Co, 1958.
20. Barrett CR, Nix WD, Tetelman AS. The principles of engineering materials. Englewood Cliffs, NJ;Prentice-Hall Inc, 1973.
21. American Society for Metals. Ductility. Papers presented at a Seminar of the ASM. October 14-15.1976, ASM Metals Park, Ohio, 1978.

*H.Mohammed Al-Tahawi