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Effect of Metal Fillers on Thermal Conductivity of Acrylic Base Complete Dentures

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Abstract:
Dental material research has entailed creating new and improved materials for prosthetic and restorative purposes, as well as modifying current materials. A number of studies on the use of fillers for strengthening denture base resin demonstrated an important enhancement in its physical properties. The purpose of this study is to prepare heat-curing PMMA denture base composites containing micron-size silver, alumina, and Chrome cobalt alloy filler particles separated with three different percentages in PMMA composite and investigate their thermal conductivity. In the dental application, improving the PMMA denture base can be provided by using several different filler loadings. **Materials and Method**: This research explored the preparation of PMMA denture base materials enhanced with silver, alumina, and chrome cobalt alloy fillers. PMMA powder was combined with these metal fillers at varying concentrations (1%, 2%, and 3% by weight) and mixed with a liquid component at a 2.5:1 ratio. The mixture achieved a workable dough stage in about 15 minutes and was then molded. Curing occurred in a water bath at 78 °C for 90 minutes to ensure complete polymerization. Twelve acrylic specimens were created, each measuring 60 mm by 40 mm, with thicknesses from 0.4 mm to 5.0 mm, following ISO 1567:2001 standards for denture base preparation. This study aims to optimize the mechanical properties of denture bases through the incorporation of metal fillers. **Result:** The difference in thermal conductivity among the three concentrations of Ag, Al_2O_3, and

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CoCr is slight. The control group exhibited significantly lower average thermal conductivity values compared to the experimental groups. The thermal conductivity value of (Ag) was statistically significantly higher than that of ($Al_2 O_3$) and (CoCr).

Keywords: Metal fillers, Polymethyl Methacrylate (PMMA), thermal conductivity, silver nanoparticles, nanocomposites.

تأثير الحشوات المعدنية على الموصلية الحرارية للأطقم الاسنان المصنوعة من الأكريليك

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الملخص:

استلزمت بحوث مواد طب الأسنان ابتكار مواد جديدة ومحسنة لأغراض التركيبات الاصطناعية والترميمية، بالإضافة إلى تعديل المواد الحالية. وقد أظهر عدد من الدراسات حول استخدام مواد الحشو لتقوية راتنج قاعدة طقم الأسنان تحسينًا مهمًا في خواصها الفيزيائية. والغرض من هذه الدراسة هو تحضير مركبات قاعدة طقم الأسنان الاصطناعية PMMA المعالجة بالحرارة التي تحتوي على جزيئات حشو من الفضة والألومينا وسبائك الكوبالت الكروم بحجم ميكرون مفصولة بثلاث نسب مختلفة في مركب PMMA والتحقيق في توصيلها الحراري. في تطبيقات طب الأسنان، يمكن تحسين قاعدة طقم الأسنان PMMA باستخدام عدة حشوات مختلفة من الحشو. **المواد والطريقة:** استكشف هذا البحث تحضير مواد قاعدة طقم الأسنان PMMA المعززة بالفضة والألومينا وحشوات سبائك الكوبالت والكروم. تم دمج مسحوق PMMA مع هذه الحشوات المعدنية بتركيزات متفاوتة (1% و2% و3% بالوزن) وخلطها مع مكون سائل بنسبة 2.5:1. وصل الخليط إلى مرحلة العجين القابل للتشكيل في حوالي 15 دقيقة ثم تم تشكيله. تمت المعالجة في حمام مائي عند درجة حرارة 78 درجة مئوية لمدة 90 دقيقة لضمان البلمرة الكاملة. تم إنشاء 12 عينة من الأكريليك بقياس 60 مم في 40 مم، بسماكة تتراوح من 0.4 مم إلى 5.0 مم، وفقًا لمعايير ISO 1567:2001 الخاصة بتحضير قاعدة طقم الأسنان. تهدف هذه الدراسة إلى تحسين الخواص الميكانيكية لقواعد

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أطقم الأسنان من خلال دمج الحشوات المعدنية. **النتيجة:** كان الفرق في الموصلية الحرارية بين التركيزات الثلاثة لكل من Ag وAl_2O_3 وCoCr طفيفًا. أظهرت مجموعة التحكم متوسط قيم توصيل حراري أقل بكثير مقارنةً بالمجموعات التجريبية. وكانت قيمة التوصيل الحراري لـ (Ag) أعلى بكثير من الناحية الإحصائية من قيمة (Al_2O_3) و(CoCr).

الكلمات المفتاحية: الحشوات المعدنية، بولي ميثيل ميثاكريليت (PMMA)، الموصلية الحرارية، جسيمات الفضة النانوية، المركبات النانوية.

Introduction

PMMA is the best option for denture bases because of its improved aesthetic appeal and mouth stability, even if there are many other polymeric materials available. As a result, PMMA remains the preferred material for a variety of orthodontic gadgets and detachable prosthesis. PMMA has been widely used in the production of denture bases since the middle of the 1940s, making it the preferred choice (Alsharif et al., 2024).

The most important biological feature is biocompatibility, which i s the ability of a material to operate in a biological environment w ith a favorable host reaction (Gautam, R et al., 2012). Even though properly designed heatcured PMMA has very few bi ocompatibility issues, the presence of uncured or residual monom ers in the cured denture foundation has been linked to tissue infla mmation, cytotoxicity, and mucosal irritation (Braun, K.N et al., 2003; Jorge, J.H., 2003; Lung, C.; Darvell, B., 2005). It demonstrates notable teeth adhesion (Palitsch et al., 2012), remains insoluble in body fluids, is relatively simple to manipulate, exhibits a favorable aesthetic appearance (Anusavice, 2003), and maintains color stability (Bayindir et al., 2012). Furthermore, PMMA-based materials find preference in various biomedical applications, such as intraocular lenses (Shtilman, 2003), orthopedic surgery bone cement (Kuhn, 2005), and removable dentures (Preshaw et al., 2011).

By adding alumina, an oxide ceramic, polymerization shrinkage can be decreased and thermal conductivity and endurance can be enhanced. Asar NV, et al., 2013; Panyayong W, et al., 2002; Atla J, et al., 2013; Ellakwa AE, et al., 2008; Messersmith PB, et al., 1998. When compared to one of its component materials, a

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composite structure may exhibit notable advantage in certain aspects. In 1994, Vallittu PK; in 2013, Anusavice KJ, 2012. SiC and Si3N4 are more durable than oxide ceramics due to their high covalent bond content, superior thermal properties, and biocompatibility, which enables their usage in dental prosthesis and medical implants (Bal BS, Rahaman MN, 2012). S. Barillet et al. (2010). They have the capacity to be applied in dental settings (28). Tham WL, et al., 2010; Shyang CW, et al., 2008; Gutteridge DL, 1988; Mazzocchi M, Bellosi A, 2008; Xu HH, et al., 2003.No research has examined the use of SiC, Si3N4, TiO2, ZrO2, or hydroxyapatite (HA) ceramic powders to improve the denture base material's heat conductivity.

Due to PMMA's insulating qualities, older people who wear dentures constructed of this material frequently have trouble perceiving temperature. The oral mucosa's temperature can range from 0 to 70°C when eating hot or cold foods before leveling off at the body's typical temperature. Denture users may find this fluctuation especially troublesome since the PMMA denture base material that covers the palate mucosa, either whole or partially, may impair their capacity to sense these temperature shifts. Because the user may not be able to accurately sense the temperature of food and drinks, this impairment may result in dissatisfaction with the prosthesis and raise the risk of burns or discomfort from too hot or cold products. To mitigate these issues, incorporating denture bases with higher thermal conductivity can help protect the health of the oral tissues and enhance the overall satisfaction of the user with their prosthetic device (Mohd Farid, et al., 2022; - Alqutaibi, A. Y, et al., 2023).

Several changes to the materials and design of prosthetics can greatly enhance taste perception in those wearing dentures. According to research, the materials used to make dentures might affect the wearer's overall comfort as well as their taste perception. For example, by promoting a more organic contact between the prosthesis and the oral mucosa, the use of denture bases that permit improved thermal and tactile stimulation can improve taste perception. This improvement can lead to a more satisfying eating experience, as the user is better able to detect flavors and temperatures of food (Stefanczyk, M.M., Oleszkiewicz, A, 2020). Several materials with high thermal conductivity have been introduced to improve the thermal conductivity of polymethyl methacrylate (PMMA). Traditionally, the traditional denture base

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material has been mixed with metal powders including cop-per, aluminum, and silver. These metals are renowned for having exceptional thermal qualities, which can greatly enhance PMMA's capacity for heat transfer. However, a volumetric addition of roughly 25% of these metal powders is necessary to provide a significant improvement in thermal conductivity more precisely, a 4.5-fold gain. Although this large increase in filler content improves thermal efficiency, it has a drawback in that it reduces tensile strength by about 35% (Hidalgo-Manrique, 2019). Alternatively, thermally conductive ceramics may be more suitable additives compared to metal powders, as many ceramics exhibit thermal conductivity similar to metals (Harris, 1995). Additionally, ceramic fillers have low density, thereby minimally affecting the weight of the prosthesis. The remarkable thermal conductivity of silicon carbide (SiC) is known to significantly outperform that of conventional materials like copper, alumina (AlO_3), and aluminum nitride (AlN). In particular, SiC has thermal conductivity values between 120 and 180 W/(m·K), whereas copper, which is renowned for its superior thermal qualities, has a thermal conductivity of about 400 W/(m·K) under ideal circumstances. However, SiC is a better option for many cutting-edge engineering applications due to its performance in high-temperature applications and its capacity to maintain structural integrity under harsh circumstances. SiC's favorable position in thermal management applications is further highlighted by the fact that aluminum nitride and alumina have thermal conductivities of roughly 170 W/(m·K) and 30 W/(m·K), respectively (NSACO Inc. - Machining of Hard Materials, 2022).
Additionally, SiC is characterized by its high hardness, thermal stability, and low density (Cappi et al., 2010). Due to its strong covalent bonding, SiC exhibits superior durability compared to oxide ceramics, along with favorable thermal properties, biocompatibility, and cytocompatibility, making it suitable for medical implants and prostheses (Atla et al., 2013). Alumina, on the other hand, has been utilized to reinforce acrylic resins (Ellakwa et al., 2008) and is recognized as the strongest and most rigid among oxide ceramics (Patra et al., 2009). Its exceptional hardness, excellent dielectric properties, good heat resistance, and thermal characteristics contribute to its wide range of applications (Jagger et al., 1999). Numerous studies have been conducted to enhance the mechanical properties of denture base materials

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through the incorporation of various metal and non-metal fillers (John et al., 2001; Yadav et al., 2012). However, a significant drawback of this material lies in its physical properties, particularly its remarkably low thermal conductivity (Brady et al., 1974), which has received relatively little attention.

Thermal conductivity refers to a material's ability to conduct heat. The efficient conduction of heat by the denture base plays a crucial role in determining overall patient satisfaction due to temperature variations in foods and beverages. In 1981, Kapur and Fischer conducted a study confirming that the thermal conductivity of the denture base significantly influences parotid gland secretions and, consequently, the sense of taste. They observed that when the temperature of the palatal soft tissue increased, there was an increase in parotid secretion when metal bases were used. However, when acrylic bases were employed, there was no corresponding increase in parotid secretions. This study aimed to assess the effect of metal fillers on some properties of acrylic base complete denture, comparing three types of fillers with different concentrations.

Materials and Methods

The materials used in this research are PMMA powder (Mw, 996.000 g/mol; (Merck chemical, Darmstadt, Germany), and (Silver (Ag), Alumina (Al_2O_3) and Chrome cobalt alloy (CoCr) fillers particles). The PMMA denture base material was prepared using powder components mixed with the liquid component. The powder components were comprised of PMMA powder, metal fillers as impact modifier particles. (Ag), (Al_2O_3) and (CoCr) powder were added to PMMA powder and mixed with 1, 2 and 3 wt %, respectively. Each of the powder mixture components was mixed with the liquid component by hand mixing, respectively. The mixing of powder mixture to liquid medium (P/L) ratio was set at 2.5:1, according to standard dental laboratory usage. The composite reached the dough stage (working stage) for easy forming of the paste around 15 min, and the mixture was packed into the specific mold. The curing process is carried out by placing the mold in a water bath. The temperature of water bath was kept at 78 °C for 90 min to complete the heat polymerization. The mold was removed from the water bath and then left to cool slowly to room temperature. The samples were removed from the mold, then, trimmed and polished by using emery paper 240. This procedure is

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in accordance to ISO 1567:2001 dentistry-denture base polymer standard method for preparing a conventional denture base in a dental laboratory.
Twelve acrylic specimens in three groups with dimensions of the length 60 mm × 40 mm width, having a thickness range from 0.4 mm to 5.0 mm were prepared using conventional flasking and packing in gypsum molds, (3 specimens and one control for each group).

Thermal conductivity test

Thermal conductivity was measured in a 70-75 C temperature range corresponding to possible food and beverage temperatures using the transient hot bridge (THB) method. Qianli Super Cam X thermal imaging camera is used for temperature measurement. This method is suitable for measuring the heat conduction of polymer materials. While measuring the thermal conductivity of the prepared samples in the THB-100 tester, an IR camera specifically designed for detecting thermal hot-spots on the surface of the samples, then installing the dedicated software that is downloadable at the bottom of this product page.
Thermal conductivity was calculated as follows:
An illustration describing the thermal conductivity of a material in terms of the flow of heat through it is provided above. In this example, $Temperature_1$ is greater than $Temperature_2$. Therefore, the thermal conductivity can be obtained via the following equation:

Mathematical analysis method

After obtaining the data, thermal conduction was calculated using Equation (Cengel & Ghajar, 2014):

$$\frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x} \qquad (1)$$

Where:
$\frac{\Delta Q}{\Delta t}$ = The rate of heat transfer (J/s).
A = Area of the material (m^2).
Δx = Thickness of the material (m).
k = Thermal conductivity coefficient of the material [W/m °C].
ΔT = The difference in temperature applied between the endpoints (°C).

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The results were analysed according to the values of ΔQ/Δt [J/s] obtained for an applied ΔT.

The thermal conductivity coefficient corresponds to the amount of thermal energy, that passes through 1 m^2 of surface in a second when the difference in temperature between the two sides of the material is 1 °C. conduction heat.

Results and Discussion

Heat conduction was measured at four intervals: one minute, two minutes, three minutes, and four minutes for each sample. The results of this study showed that the change in heat conduction varied over time, as well as with the percentage of added fillers. The control group exhibited lower heat conduction compared to samples mixed with silver (Ag), alumina (Al_2O_3), and chrome cobalt (CoCr) fillers in different proportions. The findings indicate that incorporating metallic fillers such as Ag, AlO_3, and CoCr increased the heat conduction of acrylic, as presented in Table 1.

Table 1. The change in the heat conduction (J/s) of acrylic mixed with different concentrations of Ag, Al_2O_3 and CoCr

Sample	1min	2min	3min	4min
Control	0.267	0.214	0.181	0.156
1% Ag	5.008	3.84	3.17	2.56
2% Ag	9.755	7.176	6.018	5.121
3% Ag	14.349	10.512	8.343	7.174
1%Al_2O_3	0.583	0.44	0.369	0.313
2%Al_2O_3	0.937	0.722	0.598	0.538
3%Al_2O_3	1.219	0.914	0.787	0.656
1% Cocr	0.41	0.307	0.2538	0.2022
2% Cocr	0.572	0.422	0.331	0.2705
3% Cocr	0.66	0.5028	0.418	0.356

For the silver filler, heat conduction started at 5.008 J/s in the 1% silver sample after one minute and reduced over time, reaching 2.56 J/s after four minutes. The heat conduction in the 2% silver sample increased to 9.755 J/s, then decreased to 5.121 J/s after four minutes. The highest value recorded was 14.349 J/s in the 3% silver sample at one minute, decreasing to 7.174 J/s at four minutes, as

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shown in Figure 1. These results were similar to those obtained by Silva et al. (2022), who reported heat conduction within the range of 0.5 ± 0.06 J/s to 12.92 ± 2.15 J/s for specimens fabricated with 2 wt% silver nanoparticles at varying thicknesses (2 mm and 8 mm). Another study, which provided lower results compared to the present study, reported values ranging from 3.5421 to 3.8643 for cylindrical-shaped samples modified with 2 wt% silver nanoparticles (Hamedi-Rad et al., 2014). Neither study provided information about the duration of heat flow, only mentioning the ratio and thickness.

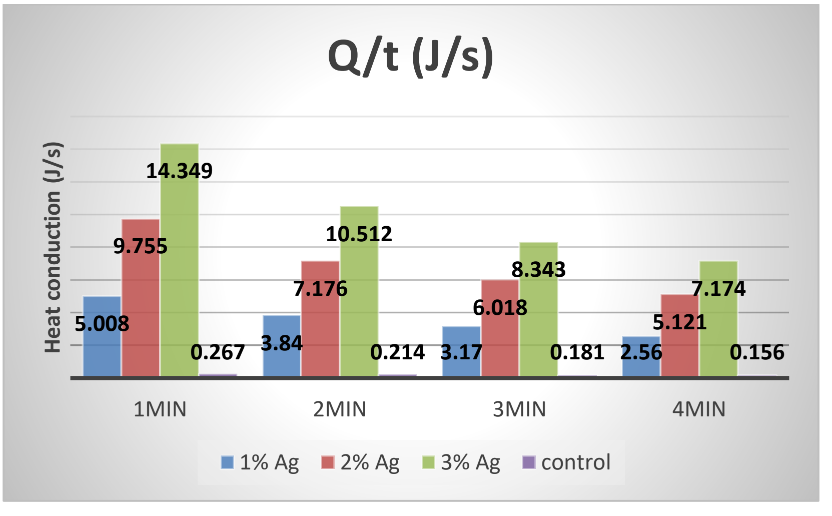

Figure 1. The change in the heat conduction (J/s) of acrylic mixed with different concentrations of Ag.

The results indicate that as the concentration of silver filler increases, the rate of heat conduction also increases. However, over time, the rate of heat conduction decreases for all concentrations. This behavior is consistent with Fourier's law of heat conduction, which states that the rate of heat transfer is directly proportional to the temperature gradient. As the temperature gradient decreases over time, the rate of heat conduction also decreases. The addition of silver to acrylic enhances heat conduction, attributed to the high thermal conductivity coefficient of silver, resulting from its abundance of free electrons. When silver molecules are incorporated with acrylic, the molecules of both materials interact, facilitating the transfer of thermal energy from one side to the

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other. Moreover, the thermal conductivity of acrylic increases proportionally with the concentration of silver particles.
Regarding the Al_2O_3 filler, the 3% Al_2O_3 sample recorded the highest heat conduction value of 1.219 J/s, followed by the 2% Al_2O_3 sample at 0.937 J/s, and the lowest value of 0.583 J/s for the 1% Al_2O_3 sample after one minute, as illustrated in Figure 2. Similar to the silver filler, heat conduction decreased over time for all concentrations of Al_2O_3 filler. These results are higher than those obtained by Yesildal et al. (2021), who reported values of 0.27 ± 0.003 and 0.31 ± 0.002 for aluminium fillers (60 × 50 × 3 mm) with a volume ranging from 5% to 25%.

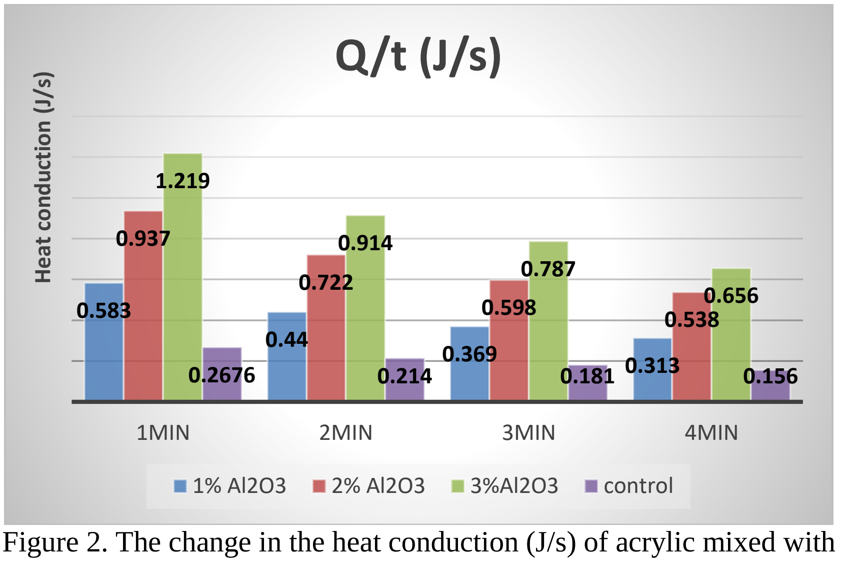

Figure 2. The change in the heat conduction (J/s) of acrylic mixed with different concentrations of Al_2O_3

Although the thermal conductivity of acrylic increases with the rise in the percentage of Al_2O_3 filler, it remains lower than that achieved with silver addition. This difference is due to the lower thermal conductivity of aluminum compared to silver. Silver has a higher thermal conductivity coefficient due to its abundance of free electrons, allowing it to conduct heat more effectively than aluminum.
When incorporating CoCr into acrylic, the rate of heat conduction was lower than that achieved with Al_2O_3 and Ag but higher than in the control group. An addition of CoCr at a rate of 1% resulted in a heat conduction value of 0.41 J/s after one minute, decreasing to 0.2022 J/s within four minutes. However, increasing the percentage of CoCr to 3% led to an increase in the heat conduction rate,

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reaching 0.66 J/s after one minute, as shown in Figure 3. Despite the lower heat conduction compared to Al_2O_3 and Ag, adding CoCr results in higher heat conduction than the control group. This indicates that CoCr enhances the heat conduction of acrylic to some extent.

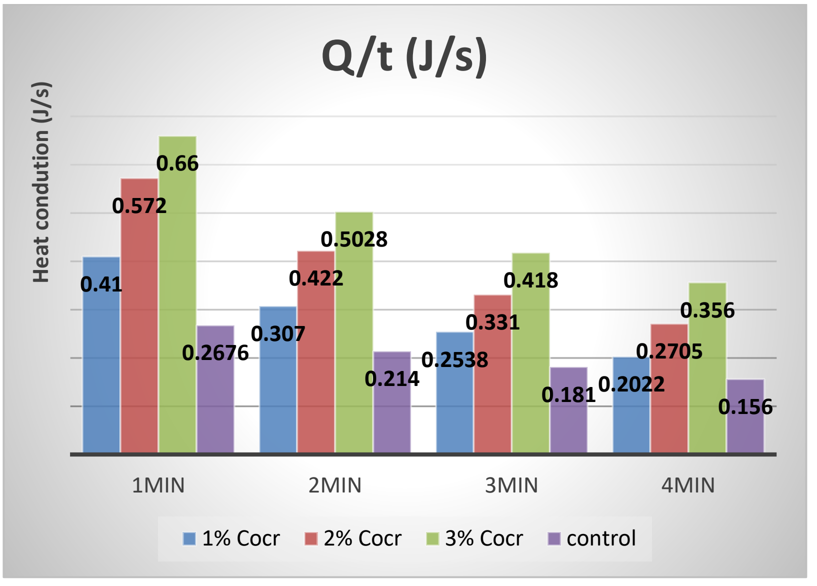

Figure 3. The change in the heat conduction (J/s) of acrylic mixed with different concentrations of CoCr

The study findings indicate that incorporating fillers such as Ag, Al_2O_3, and CoCr, which possess high thermal conductivity, into the denture base resin can improve the thermal conductivity of acrylic. This improvement is due to the high thermal conductivity of Ag compared to Al_2O_3 and CoCr. Since Ag is an excellent conductor of heat, it significantly enhances the heat transfer properties of the composite material. While Al_2O_3 and CoCr may not have as high thermal conductivity as Ag, they still contribute to improved thermal conductivity compared to the control group. Therefore, selecting fillers with high thermal conductivity, such as Ag, Al_2O_3, and CoCr, can be beneficial for denture base resin where heat transfer is a vital consideration.

Conclusion

The findings underscore the ongoing need for improvements in dental materials, especially in the area of dental composites. In an effort to provide patients with a more dependable and long-lasting

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solution, continuous research and development efforts are made to improve the general properties and efficiency of denture materials. The use of metal fillers powder to meet denture base resin's thermal conductivity requirements has shown promise. Additionally, the research investigates the influence of metal fillers on thermal conductivity, identifying an increase related to the inclusion of these types of fillers. Although acrylic resin has low thermal conductivity, the results of the current study showed that incorporating filling materials of different weights into the denture base resin increases the thermal conductivity in proportion to the filling percentages.

In summary, a variety of techniques are employed in seeking better denture base materials, such as investigating substitute polymers and enhancing the heat conductivity of metal fillers. Continuous research is still necessary to overcome present challenges and promote progress in the dental prosthesis field.

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