Resinous Denture Base Fracture Resistance: Effects of Thickness and Teeth

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Purpose: Fracture is a frequent complication of resinous prostheses. The purpose of this study was to evaluate the effect of thickness on flexural strength of a resinous prosthesis containing a prosthetic tooth. ***Materials and Methods:*** Beam-shaped specimens 65-mm long, 12-mm wide, and 1, 2, 3, 4, or 6 mm in thickness were made from high-impact strength polymethyl methacrylate denture base material, each containing a resin-based molar prosthetic tooth at the center of the beam. A group of 3-mm-thick specimens without a prosthetic tooth (n = 7) were also made. Specimens were aged artificially, loaded in three-point flexure, examined fractographically, and analyzed. ***Results:*** The 1- and 2-mm-thick beams underwent considerable deformation at low loads. Maximum loads varied considerably from 0.6 kg (1-mm beams) to 38 kg (6-mm beams). The 3-, 4-, and 6-mm beam groups all underwent brittle fracture, with mean relative flexural strengths of approximately 73 MPa. Denture teeth reduced the relative flexural strength of resin beams by 0.7×. Fracture initiation sites were generally at tiny surface defects, but did not directly involve denture teeth. Denture resin fracture toughness was 3.2 MPa $m^{1/2}$, and modulus of rupture was 104 MPa. ***Conclusion:*** Denture teeth substantially decreased the strength of resinous beams. Increased thickness markedly increased the load-bearing capacity of resinous beams containing denture teeth. Beams less than 2 mm in thickness with denture teeth were weakened substantially more than comparable beams of 2 mm or more in thickness. Surface finish was of critical importance. Fracture toughness was calculated fractographically, facilitating future forensic examination of clinically failed resinous prostheses. *Int J Prosthodont 2012;25:53–59.*

Fracture is a stunningly frequent complication of resinous prostheses.[1–10] Patients with fixed or removable resinous prostheses may exert considerable masticatory force.[11–13] Masticatory function is thought to produce slow crack growth in resinous denture bases through cyclic flexural fatigue.[14–18] Once a crack reaches a critical size, applied stresses may initiate long crack growth, causing sudden catastrophic failure.[19] Factors that increase stress concentrations are likely to predispose prostheses to fracture. Abrupt changes in contour associated with frenal notches; discontinuities associated with prosthetic teeth, pinholes, defects, or inclusions; and residual stresses may all localize stresses.[7,10,16,18,20–24] Fractures often occur close to overdenture abutment teeth or implants,[7,10,23–25] which are obvious causes of stress localization. Fractures may also occur when a patient drops a prosthesis onto a hard floor or an empty basin during hygiene procedures.[1,16] In these cases, impact stresses may cause abrupt long crack growth. Likewise, such fractures are likely to be initiated in areas of stress concentration.[15,16,18]

New highly cross-linked polymeric materials, stronger than the long-used methyl methacrylate resins, have become widely available. Improved processing techniques may offer additional strength and uniformity within the denture base.[26] Inclusion of metal or fiber reinforcements holds much promise, but has not yet received clinical validation.[27–29] Discontinuities

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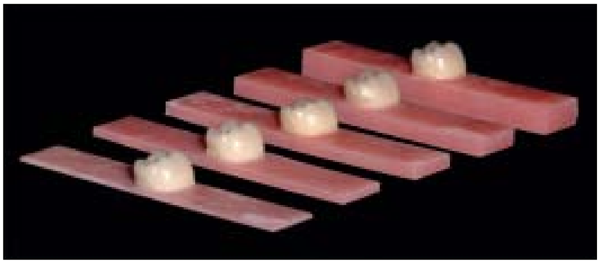

Fig 1 Resin beam specimens. All beams were 65 mm in length and 12 mm in width. Thicknesses varied among groups (1, 2, 3, 4, or 6 mm).

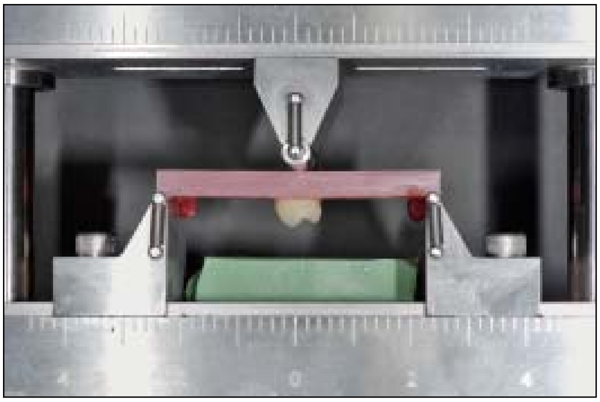

Fig 2 A beam during testing in three-point flexure. The intaglio side of the beam was placed in compression and the occlusal surface was placed in tension.

introduced by metal reinforcements can increase stiffness and strength, but may also have some counterproductive effects in increasing stress concentrations and decreasing the volume of the resinous bulk of the prosthesis.[24,30] Fiber reinforcements can complicate processing techniques and create undesirable surface roughness if they meet the surface of the prosthesis. Research has focused on improving the adhesion of denture teeth to denture base resins. However, despite these improvements, fractures still occur.

Until effective reinforcements are validated clinically, knowledge of the effect of base thickness on fracture resistance will guide the clinician in choosing an appropriate thickness of denture base resin. However, base thickness may be constrained by abutments, denture teeth, and patient comfort. Many studies have measured the strength and toughness of denture base polymers.[23,31–35] However, such studies rarely included key stress-concentrating elements such as prosthetic teeth. Therefore, it is difficult to relate such studies to clinical situations. Other studies have included a complex "natural" geometry[14,18]; however, this prevents the isolation of specific variables, such as base thickness, from the influence of a specific geometric conformation. Therefore, a study evaluating the effect of thickness on strength of a resin beam containing a stress-concentrating discontinuity associated with a denture tooth was conducted.

The purpose of this study was to evaluate the effect of thickness of a resinous beam containing a prosthetic tooth on flexural strength.

Materials and Methods

Experimental Model

Because stress analyses have indicated that tensile stresses are predominate on occlusal aspects and polished surfaces of dentures,[12,18,20,36–38] the current system used a three-point beam design to place the simulated intaglio surface in compression and the occlusal aspect of the beam in tension (Figs 1 and 2). Because fractures frequently involve stress-concentrating elements such as prosthetic teeth, a prosthetic tooth was placed in the central portion of each beam.[4–6,10,18,21–24] Although most resinous prostheses contain multiple prosthetic teeth, a single tooth was used so that the effects of a single variable (denture base thickness) on a well-defined area of stress concentration could be evaluated. This was simpler than much more complex real-life geometries, but the effects of a prosthetic tooth and denture base thickness could be isolated and elucidated. For flexural testing, beam-shaped specimens 65 mm in length, 12 mm in width, and 1, 2, 3, 4, or 6 mm in thickness were made.[19,35] Prior studies on span-to-thickness ratios used for testing brittle materials in three-point flexure suggested that a ratio of 5:1 can be sufficient.[39] Because the beams used in this study contained denture teeth, higher span-to-thickness ratios were used to decrease the influence of complex shear and compressive forces.[39] Additionally, the authors validated these ratios, all exceeding 10:1, in a pilot study. The beam thicknesses were chosen so as to reasonably represent the range of thicknesses of typical denture bases.[39] Seven beams were made in

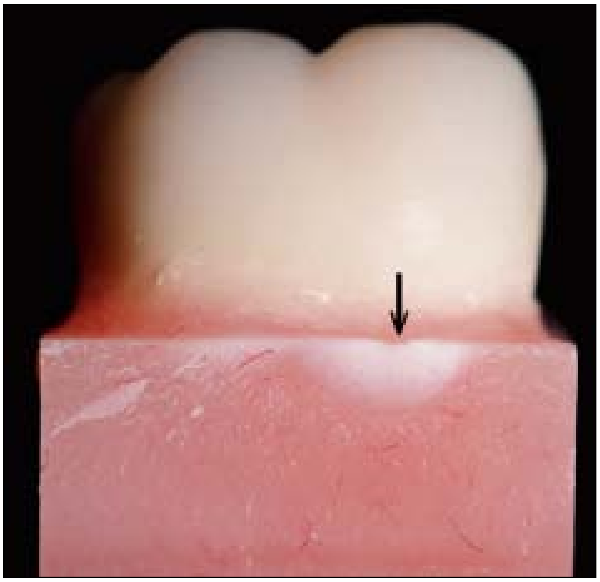

Fig 3 A fractured 6-mm-thick specimen. The fracture occurred close to the denture tooth but did not involve the tooth-base interface. The arrow indicates the source of failure, or crack nucleation. The shape and general appearance of the white semicircular fracture surface surrounding the source of failure includes mirror, mist, and hackle regions. Radial crack branching can be seen on the rest of the pink surface. Once nucleated, a crack propagates slowly to produce a very smooth flat region (mirror region). As the crack continues to spread, it accelerates toward its terminal velocity and increases in surface roughness (mist region). As the crack spreads further, the excursions become larger and proceed further from the principal fracture plane (hackle region). As additional spreading occurs, deviations become large enough to nucleate and propagate secondary cracks and branching.

each thickness; the sample size was chosen following estimation of variance from the pilot study and power calculations using the Cohen *d*. An additional seven specimens of 3 mm in thickness were fabricated but without prosthetic teeth so that the flexural strength or modulus of rupture of the resinous denture base material could be calculated.

Specimen Fabrication

Beam patterns were generated using Rhinoceros 4.0 Nurbs modeling software (McNeel North America). Wax beams were printed using VisiJet DP 200 casting material (3-D Production System, 3D Systems). A resin-based molar denture tooth (mandibuar right first molar; SR Postaris DCL mold PL2, Ivoclar Vivadent) was placed in the center of each wax beam and secured using a 0.5-mm wax collar (Figs 1 to 3). Thus, the resin bodies of the beams were of full thickness. Natural gingival anatomy was not simulated to avoid additional complex stress concentrations, so the collars more closely simulated typical lingual, palatal, or proximal contours rather than facial contour. The specimens were invested using type 3 dental stone (Modern Materials). An injection-molding technique was used to pack and polymerize a high-impact modified polymethyl methacrylate denture base material according to the manufacturer's instructions (SR-Ivocap High Impact, Ivoclar Vivadent).

Artificial Aging

Specimens were stored in filtered tap water for 10 days after fabrication to ensure that the specimens were hydrated before being subjected to artificial aging by thermocycling and mechanical testing.[19] Artificial aging by thermocycling was used to fatigue the specimens before testing because prosthesis failure is thought to be influenced by mechanical fatigue. Differences in coefficients of thermal expansion between the prosthetic tooth and base resin combined with specimen geometry applied stresses to the specimens as they expanded and contracted in water. The specimens were artificially aged by thermocycling from 5°C to 55°C for 1,000 cycles with a travel time of 30 seconds and dwell time of 120 seconds. This unusually long dwell time was chosen to ensure that these large test specimens had time to heat up and cool down within each cycle.

Mechanical Testing

A three-point beam design was used to place the simulated intaglio surface in compression and the occlusal aspect of the beam in tension because photoelastic stress analysis has indicated that tensile stresses are predominate on occlusal aspects and polished surfaces of dentures (Fig 2).[18,20,36–38] Wet specimens[19] were mounted in three-point flexure and loaded at a crosshead rate of 0.1 inch per minute with a span of 60 mm using a screw-driven universal testing machine (model 1122, Instron). The maximum load was recorded in N. Relative flexural strengths (RFS) were calculated in MPa as follows: $RFS = 3Fl / (2bd^2)$, where F = force, l = distance between supports, b = width, and d = thickness. Because the teeth likely altered stress distributions and prevented midpoint fracture, the term *relative flexural strength* was used.

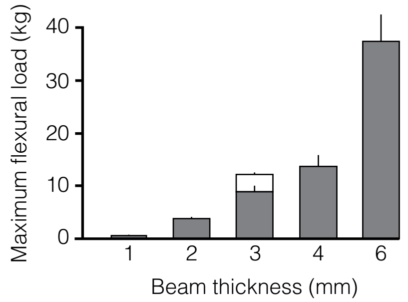

Fig 4 Maximum flexural loads of acrylic resin beams. The solid black bars represent beams with denture teeth; the white bar superimposed on the 3-mm-thick group represents the 3-mm-thick beams without denture teeth. Increased thickness markedly increased the load-bearing capacity of resinous beams containing denture teeth. The presence of a denture tooth substantially decreased the load-bearing capacity of resinous beams.

The fracture surfaces of the tested beams were examined using a variety of light microscopic techniques (brightfield, darkfield, Nomarski, and polarization) to identify and study the radii of the fracture origin and fractographic patterns, such as the smooth mirror zone, mist zone, and hackle fracture zone. Measurements were made using a toolmaker's microscope (Unitron) equipped with digital positioners calibrated to 0.1 μm (Boeckler). In specimens where these features could be discerned, and which underwent brittle failure, fracture toughness, K_{IC} (MPa $m^{1/2}$), was calculated using methods previously described for brittle dental ceramic materials using the equations listed in of the publication by Scherrer et al.[40,41]

Data Analysis

Mean loads and relative strengths along with their associated standard deviations were calculated for each beam thickness group and plotted. In the event that statistical analysis was useful, one-way analysis of variance (ANOVA) was performed to determine whether significant differences existed among the different thickness groups ($P < .05$). The Tukey multiple comparisons test was then used to determine which beam thicknesses differed from one another.

Results

Fractography

The 1- and 2-mm-thick beams did not fracture during flexural testing. Maximum supported loads were recorded. These beams underwent considerable elastic deformation of more than 10× their thickness without fracturing, at which time the tests were terminated. No measurable plastic deformation was evident on load versus time plots. The deformation was almost completely recovered when the specimens were unloaded, indicating that elastic behavior was dominant.

The 3-, 4-, and 6-mm-thick beams underwent brittle fracture, with no measurable plastic deformation evident on the load versus time plots. The fracture-initiating flaws and the smooth mirror regions of slow crack growth could be clearly identified on the 4- and 6-mm-thick specimens. The fracture-initiating flaws were related to minor changes in surface texture, but not to color fibers or processing defects. Fractures tended to occur within 0.5 mm of the denture teeth, but only rarely right against the denture teeth (Fig 3). This indicated that the bond between tooth and resin largely withstood artificial aging by thermocycling. Fracture sites were distributed between the buccal and lingual aspects of the prosthetic teeth, indicating that the minor asymmetry of the prosthetic teeth was unimportant in influencing fracture initiation.

Fracture toughness could be calculated for the resinous denture base material in four of the 6-mm-thick beams. The mean fracture toughness, K_{IC}, was 3.2 ± 0.3 MPa $m^{1/2}$.

Maximum Load

Maximum loads varied considerably (over almost two orders of magnitude) from 0.6 kg for the 1-mm-thick beams to 38 kg for the 6-mm-thick beams (Fig 4). Despite the presence of the prosthetic teeth, the 4-mm-thick beams supported four times more load than the 2-mm-thick beams. Among the beams containing prosthetic teeth, ANOVA revealed differences in maximum load ($P < .0001$), and multiple comparisons testing revealed that all thickness groups differed from one another ($P < .05$).

The 3-mm-thick beams without teeth, fabricated to measure modulus of rupture or the true flexural strength of the base resin, supported 1.4× more load than comparable beams with denture teeth. Thus, the presence of denture teeth substantially reduced the load-bearing capacity of the resin beams. The slopes of load versus crosshead displacement plots for the

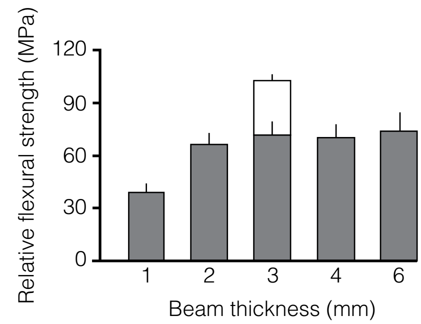

Fig 5 Relative flexural strength of acrylic resin beams. The solid black bars represent beams with denture teeth; the white bar superimposed on the 3-mm-thick group represents the 3-mm-thick beams without denture teeth. The 2-, 3-, 4-, and 6-mm beam groups with denture teeth did not differ in relative flexural strength; the 1-mm-thick beams behaved in a mechanistically different manner. The presence of a denture tooth substantially decreased the relative flexural strength of resinous beams.

3-mm-thick beams with and without denture teeth did not differ measurably, indicating that these beams largely behaved in a mechanistically similar manner and that the span-to-thickness ratio was sufficient.

Relative Flexural Strength

ANOVA revealed overall differences in relative flexural strength among the beams containing prosthetic teeth ($P < .0001$). However, multiple comparisons testing revealed that the 2-, 3-, 4-, and 6-mm-thick beams did not differ significantly from one another, suggesting that the presence of a denture tooth influenced these beams in a mechanistic manner despite their different thicknesses and thickness-to-span ratios ($P < .05$) (Fig 5). The 1-mm-thick beams had a significantly lower relative flexural strength than all other groups, indicating that the denture tooth influenced the 1-mm-thick beams in a mechanistically different manner.

The modulus of rupture, or flexural strength, and its associated standard deviation for the 3-mm-thick beams without denture teeth was 104.4 ± 7.8 MPa. Hence, the addition of a prosthetic tooth weakened the 3-mm-thick beams by approximately 25% (Fig 5), even though crack propagation only rarely followed the resin-tooth interface.

Discussion

How thick should a denture base or a connector of a treatment partial denture be? This experiment provides several insights. First, the 1- and 2-mm-thick beams deformed substantially under typical masticatory loads,[11–13] suggesting that these thicknesses are inadequate for unreinforced stress-bearing denture bases or connectors. Deformation is generally thought to be a most undesirable property of denture bases or major connectors. Second, the markedly lower relative flexural strength of the 1-mm-thick beams (Fig 5) suggests that a thickness of 2 mm or more is necessary for clinically meaningful mechanical performance. Together, these data indicate that thicknesses of more than 2 mm are desirable. Pertinently, the 4-mm-thick beams supported 3.9× and 1.6× more load than the 2- and 3-mm-thick beams, respectively, so a small increase in thickness can have a profound effect on load-bearing capacity. However, few patients tolerate palatal bases that are 4-mm thick. Unfilled or unreinforced resinous materials may have inherent limitations as denture base materials.

Caution must be used in comparing the loads borne by these test beams to clinical situations. However, the beams have some relevance to the dimensions of prostheses. The test span for the beams was 60 mm, not unduly different from the cross-arch span of a typical complete denture.[33] The beam width of 12 mm was broadly comparable in size to a connector in a treatment partial denture or to the width of a distal cantilever of an implant-supported prosthesis. The loads applied were within the range of routine masticatory loads. However, substantial differences in geometric conformation between these planar beams and the complex geometry frustrate general comparison. For example, the curved forms of denture bases may act as U-beams.

One unusual clinical study on denture deformation during masticatory function found that increasing denture base thickness from 1 to 2 mm was not necessarily accompanied by a reduction in thrust to the palatal vault or in bending moments within the denture.[12] However, stiffer cobalt-chromium bases substantially reduced thrust and bending moments.[12] It is possible that the extreme flexibility of the 1-mm-thick resin base allowed considerable deformation and limited the patients' abilities to masticate. These findings also suggest that bases should be more than 2 mm in thickness.

The addition of prosthetic teeth substantially weakened the resinous beams (Figs 4 and 5), even though the teeth were placed on the surfaces of the beams without decreasing their thickness. Furthermore, the fractures rarely involved the resin-tooth interface, suggesting that this interface remained intact despite storage and artificial aging by thermocycling. These findings suggest that the resin-tooth bond was not a weak link in this study. Therefore, stronger bonding between the resin and tooth would be unlikely to improve beam strength. One possible future avenue for strength improvement might be to more closely match the mechanical properties of denture base materials to those of highly filled denture teeth. These findings also indicate that stress concentration by the denture teeth in the adjacent resin likely provided the dominant weakening effect.

The fracture origins, discernable in most of the 4- and 6-mm-thick beams, were almost always related to minor changes in surface texture adjacent to the prosthetic teeth. This finding emphasizes the critical importance of care in waxing, processing, and polishing resinous prostheses to create smooth surfaces, especially in the complex gingival areas adjacent to denture teeth.

In this study, elastic deformation was dominant; this was evident from the load versus time plots and from the fractography. Any plastic or permanent deformation was of too small a magnitude to be measurable. In addition, the fractured pieces of a single specimen could be seamlessly mated together. Likewise, the fractured halves of a mandibular complete denture can often be mated together when making an index for repair, suggesting that brittle fracture is a commonly encountered failure mechanism.

For the first time in the dental literature, the fracture toughness of a resinous material was calculated using fractographic analyses. Furthermore, simple light microscopy was used to identify and measure the necessary features. This finding demonstrated that forensic examination of clinically fractured resinous prostheses could provide data on clinical fracture stresses in the future.[40] The fracture toughness value obtained in this study for a high-impact material (3.2 MPa $m^{1/2}$) was higher than the value of 2.4 MPa $m^{1/2}$ previously obtained for a closely related but not high-impact material (Ivocap Plus) using a three-point flexural test of a notched beam.[23,31]

The value for modulus of rupture (104 MPA) was consistent with prior reports of 102 and 104 MPa before and after thermocycling and 81 MPa for related non–high-impact materials (SR-Ivocap and Ivocap, respectively).[32,33]

The measured fracture toughness and modulus of rupture values placed the resinous denture base material used in this study among the best of all engineering polymers in a zone coincident with that of the nylons in an Ashby plot,[42] suggesting that the potential for future improvement in unreinforced resinous denture base materials is limited. The inclusion of various reinforcing materials is a promising avenue for future improvements, especially when space for a thick denture base is unavailable.

Conclusions

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

- The presence of a denture tooth substantially decreased the strength of resinous beams.
- Increased thickness markedly increased the load-bearing capacity of resinous beams containing denture teeth.
- Beams less than 2 mm in thickness that contained denture teeth were weakened substantially more than comparable beams of 2 mm or more in thickness.
- Crack initiation usually occurred at tiny surface defects close to, but not involving, denture teeth.
- Fracture toughness was calculated fractographically, facilitating future forensic examination of clinically failed resinous prostheses.

Acknowledgments

The authors appreciate the invaluable technical assistance of Steven Pigliacelli, the generosity of Ivoclar Vivadent in providing the denture teeth used in this study, and all who have preceded them in studying the frequent and costly clinical problem of prosthesis fracture.

References

1. Hargreaves AS. The prevalence of fractured dentures. A survey. Br Dent J 1969;126:451–455.
2. Vallittu PK, Lassila VP, Lappalainen R. Evaluation of damage to removable dentures in two cities in Finland. Acta Odontol Scand 1993;51:363–369.
3. Carlson B, Carlsson GE. Prosthodontic complications in osseointegrated dental implant treatment. Int J Oral Maxillofac Implants 1994;9:90–94.
4. Darbar UR, Huggett R, Harrison A. Denture fracture—A survey. Br Dent J 1994;176:342–345.
5. Walton JN, MacEntee MI. Problems with prostheses on implants: A retrospective study. J Prosthet Dent 1994;71:283–288.
6. Chaffee NR, Felton DA, Cooper LF, Palmqvist U, Smith R. Prosthetic complications in an implant-retained mandibular overdenture population: Initial analysis of a prospective study. J Prosthet Dent 2002;87:40–44.
7. Nedir R, Bischof M, Szmukler-Moncler S, Belser UC, Samson J. Prosthetic complications with dental implants: From an up-to-8-year experience in private practice. Int J Oral Maxillofac Implants 2006;21:919–928.

8. Ogunrinde TJ, Ajayi DM, Dosumu OO. Causes and pattern of fracture of acrylic dentures among patients seen in a Nigerian teaching hospital. Afr J Med Med Sci 2007;36:365–369.
9. Gallucci GO, Doughtie CB, Hwang JW, Fiorellini JP, Weber HP. Five-year results of fixed implant-supported rehabilitations with distal cantilevers for the edentulous mandible. Clin Oral Implants Res 2009;20:601–607.
10. Gonda T, Maeda Y, Walton JN, MacEntee MI. Fracture incidence in mandibular overdentures retained by one or two implants. J Prosthet Dent 2010;103:178–181.
11. Lassila V, Holmlund I, Koivumaa KK. Bite force and its correlations in different denture types. Acta Odontol Scand 1985; 43:127–132.
12. el Ghazali S, Glantz PO, Strandman E, Randow K. On the clinical deformation of maxillary complete dentures. Influence of denture-base design and shape of denture-bearing tissue. Acta Odontol Scand 1989;47:69–76.
13. Miyaura K, Morita M, Matsuka Y, Yamashita A, Watanabe T. Rehabilitation of biting abilities in patients with different types of dental prostheses. J Oral Rehabil 2000;27:1073–1076.
14. Lambrecht JR, Kydd WL. A functional stress analysis of the maxillary complete denture base. J Prosthet Dent 1962;12:865–872.
15. Kelly E. Fatigue failure in denture base polymers. J Prosthet Dent 1969;21:257–266.
16. Beyli MS, von Fraunhofer JA. An analysis of causes of fracture of acrylic resin dentures. J Prosthet Dent 1981;46:238–241.
17. Johnston EP, Nicholls JI, Smith DE. Flexure fatigue of 10 commonly used denture base resins. J Prosthet Dent 1981;46: 478–483.
18. Vallittu PK, Lassila VP, Lappalainen Niom R. The effect of notch shape and self-cured acrylic resin repair on the fatigue resistance of an acrylic resin denture base. J Oral Rehabil 1996;23:108–113.
19. Hargreaves AS. The effect of the environment on the crack initiation toughness of dental poly(methyl methacrylate). J Biomed Mater Res 1981;15:757–768.
20. Craig RG, Farah JW, el-Tahawi HM. Three-dimensional photoelastic stress analysis of maxillary complete dentures. J Prosthet Dent 1974;31:122–129.
21. Darbar UR, Huggett R, Harrison A. Stress analysis techniques in complete dentures. J Dent 1994;22:259–264.
22. Darbar UR, Huggett R, Harrison A, Williams K. Finite element analysis of stress distribution at the tooth-denture base interface of acrylic resin teeth debonding from the denture base. J Prosthet Dent 1995;74:591–594.
23. Zappini G, Kammann A, Wachter W. Comparison of fracture tests of denture base materials. J Prosthet Dent 2003;90: 578–585.
24. Hirajima Y, Takahashi H, Minakuchi S. Influence of a denture strengthener on the deformation of a maxillary complete denture. Dent Mater J 2009;28:507–512.
25. Salvi GE, Brägger U. Mechanical and technical risks in implant therapy. Int J Oral Maxillofac Implants 2009;24(suppl):69–85.
26. Parvizi A, Lindquist T, Schneider R, Williamson D, Boyer D, Dawson DV. Comparison of the dimensional accuracy of injection-molded denture base materials to that of conventional pressure-pack acrylic resin. J Prosthodont 2004;13:83–89.
27. Vallittu PK, Lassila VP, Lappalainen R. Transverse strength and fatigue of denture acrylic-glass fiber composite. Dent Mater 1994;10:116–121.
28. Vallittu PK. A review of fiber-reinforced denture base resins. J Prosthodont 1996;5:270–276.
29. Jagger DC, Harrison A, Jandt KD. The reinforcement of dentures. J Oral Rehabil 1999;26:185–194.
30. Ruffino AR. Effect of steel strengtheners on fracture resistance of the acrylic resin complete denture base. J Prosthet Dent 1985;54:75–78.
31. Neihart TR, Li SH, Flinton RJ. Measuring fracture toughness of high-impact poly(methyl methacrylate) with the short rod method. J Prosthet Dent 1988;60:249–253.
32. Archadian N, Kawano F, Ohguri T, Ichikawa T, Matsumoto N. Flexural strength of rebased denture polymers. J Oral Rehabil 2000;27:690–696.
33. Uzun G, Hersek N. Comparison of the fracture resistance of six denture base acrylic resins. J Biomater Appl 2002;17:19–29.
34. Diaz-Arnold AM, Vargas MA, Shaull KL, Laffoon JE, Qian F. Flexural and fatigue strengths of denture base resin. J Prosthet Dent 2008;100:47–51.
35. Puri G, Berzins DW, Dhuru VB, et al. Effect of phosphate group addition on the properties of denture base resins. J Prosthet Dent 2008;100:302–308.
36. Matthews E, Wain EA. Stress in denture base. Br Dent J 1956; 100:167–171.
37. Swoope CC, Kydd WL. The effect of cusp form and occlusal surface area on denture base deformation. J Prosthet Dent 1966; 16:34–43.
38. Glantz PO, Stafford GD. Clinical deformation of maxillary complete dentures. J Dent 1983;11:224–230.
39. Jones DW, Jones PA, Wilson HJ. The relationship between transverse strength and testing methods for dental ceramics. J Dent 1972;1:85–91.
40. Kelly JR, Campbell SD, Bowen HK. Fracture-surface analysis of dental ceramics. J Prosthet Dent 1989;62:536–541.
41. Scherrer SS, Kelly JR, Quinn GD, Xu K. Fracture toughness (KI_C) of a dental porcelain determined by fractographic analysis. Dent Mater 1999;15:342–348.
42. Ashby M. Material property charts. In: Ashby M. Materials Selection in Mechanical Design, ed 4. Burlington: Butterworth-Heinemann, 2010:74–75.