Eur. J. Prosthodont. Rest. Dent., Vol.21, No. 3, pp 120-126
Printed in Great Britain

doi:10.1922/EJPRD_1219White07

A Novel Design Solution to the Fraenal Notch of Maxillary Dentures

J.A.P. White*, I.P. Bond† and D.C. Jagger‡

Abstract - *This study investigates a novel design feature for the fraenal notch of maxillary dentures, using computational and experimental methods, and shows that its use could significantly increase the longevity of the prosthesis. A two-step process can be used to create the design feature with current denture base materials, but would be highly dependent on the individual skill of the dental technician. Therefore, an alternative form of manufacture, multi-material additive layer manufacture (or '3D printing'), has been proposed as a future method for the direct production of complete dentures with multi-material design features.*

KEY WORDS: Denture, Stress Concentration, Fraenal Notch, Additive Layer Manufacture [ALM], 3D printing, Finite Element Analysis [FEA]

INTRODUCTION

Complete dentures are widely provided to replace missing natural teeth. Despite falling rates of edentulous patients, and increasing preference for implant-based treatments, the 2009 Adult Dental Health Survey reported that 6% of the UK population were still fully edentulous complete denture wearers. Globally, it is believed the need to provide treatment involving the provision of complete dentures for edentulous patients will remain for many more decades and that the cost of implants will continue to be unattainable for the majority[1].

Each complete denture is unique to the individual patient and is dependent on the anatomy of the edentulous ridges. The denture must adapt well to these anatomical features to provide a border seal adequate for retention[2], to prevent the accumulation of food and to aid the aesthetic appeal of the denture. Such inherent geometric constraint allows little scope to alter the design of the denture to provide improved functional performance. Consequently, improvements in the flexural and impact strengths of dentures have only been sought previously through modifications to the properties of the materials used for their construction. However, despite extensive research in this area, varying from rubber modifications to fibre reinforcement, failure to improve the strength and toughness of the material adequately, combined with the additional stages of construction required, has led to few methods being adopted commercially[3]. As a result, the service life of a typical maxillary denture can be as low as three years[4] and requires the additional cost of repair or replacement.

Both complete and partial dentures contain an array of notches and discontinuities that act as stress concentrations. The most problematic of these is the fraenal notch found in the maxillary denture and depicted in Figure 1. It has long been considered one of the primary contributors to denture fracture[5], but is required to accommodate the labial fraenum.

Stress concentrations can be quantified using the stress concentration factor (K_t, Eqn. 1[6]), which is the ratio between the maximum stress observed at the feature and the nominal global stress. This can be determined analytically, as derived independently by Inglis and Kolosoff[6,7,8] for an elliptical hole within an infinite plate (Eqn. 2). With a representing the half-length of the ellipse and r the tip radius, it can be observed that for a given notch length, decreasing the tip radius results in increasing stress. It is, therefore, good engineering practice to keep the external geometry of components as smooth as possible, thus avoiding the presence of small radius notches, corners and other such features. In engineering, this is done through the addition or removal of material and the technique is referred to as filleting.

However, as already stated, a denture is geometrically constrained and the technique of filleting cannot be applied directly. In light of this, the concept of 'pseudo-filleting' has been proposed. In this design feature, the fraenal notch is made from a low modulus material that is invulnerable to any notable stress concentrating effect. This low modulus region is then designed to expose the surrounding rigid material to a larger radius feature, thus removing the stress concentrating effect. The intended benefit is an increase in component load and displacement to failure, and consequential increase in total energy to failure, whilst crucially maintaining external geometry. From a clinical perspective, there may also be benefit in greater patient comfort in the region of the labial fraenum.

$$K_t = \frac{\sigma_{\text{maximum}}}{\sigma_{\text{nominal}}}$$

Equation 1.

$$K_t = 1 + 2\sqrt{\frac{a}{r}}$$

Equation 2.

---

* MEng, PhD
† BSc, PhD
‡ BDS, MSc, PhD

The aim of this study is to use a simple flexural experiment to investigate the relative performance between control and 'pseudo-filleted' notched specimens of equal external dimensions and compares the experimental results to predictions made by finite element analysis [FEA]. The article will also indicate methods of incorporating such a design feature into a complete denture, including the potential application of additive layer manufacture [ALM].

MATERIALS AND METHODS

The notched fracture toughness specimen of ISO 20795: 2008 was chosen to provide the general dimensions for a 3-point flexural specimen containing a fraenal notch. This consisted of a beam 64x8x4mm with a 3mm deep notch positioned on the tensile surface. A schematic of the experimental arrangement is provided in Figure 2. The dimensions for curvature of the notch were arbitrarily chosen to give a visually realistic, sharp fraenal notch with a tip radius of 0.5mm (Figure 3). The control specimen consisted entirely of denture base acrylic resin, including the sharp fraenal notch section, while the 'pseudo-fillet' contained a low modulus fraenal section (Figure 3, green), made from denture soft liner. This 'fraenal plug' was designed to present a 5mm radius notch tip to the global denture base acrylic resin and lie tangential to the original control notch.

Figure 1. *Prominent fraenal notch*

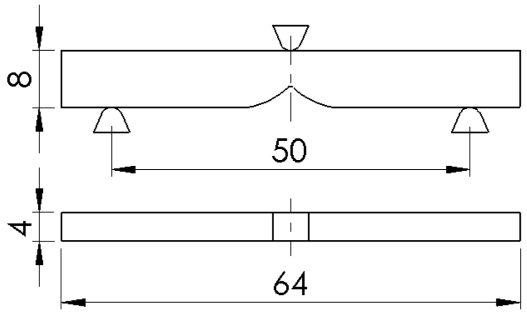

Figure 2. *Flexural arrangement adapted from ISO 20795: 2008. Dimensions in mm*

Finite Element Analysis

The notched specimen geometry of Figure 3 was modelled in a CAD programme (Autodesk Inventor 2010) and then imported into an FEA programme (Abaqus/CAE 6.9-EF1) via a SAT file as a deformable body. To complement this, an un-notched beam 64x5x4mm was also modelled to provide a value of nominal stress for use in calculating stress concentration factors. The notched specimen geometry was partitioned such that it could be meshed with swept solid quad elements and divided into differing section properties. Load pins conforming to the test standard were also modelled and imported, as discrete rigid bodies, and the coefficient of friction between them and the respective specimens was set to 0.1[9]. A mesh sensitivity study demonstrated that a global seed size of 1mm, reducing to 0.02mm directly underneath the notch, would give acceptable results. The final mesh for the notched specimen consisted of 60544 8-noded linear brick elements (C3D8R) and 464 6-noded linear wedge elements (C3D6). The un-notched beam mesh consisted of 23584 C3D8R elements and the 3-point load pins each consisted of approximately 350 4-noded linear quadrilateral elements (R3D4).

For the global body of denture base acrylic resin, the elastic modulus was taken as 2370MPa, based on additional flexural testing of Minacryl Universal denture base acrylic resin according to ISO 20795: 2008, and the Poisson's ratio was assumed to be 0.3[10]. Simple tensile testing of strips (10x5x62mm) of denture soft liner (Dentsply Eversoft) was undertaken to give a base value for the low modulus 'fraenal plug'. This was made according to the manufacturer's instructions for producing the softest lining with a powder: liquid ratio of 2:1 by volume. Reported values of modulus for soft denture liner are quite variable in the literature[11,12,13], but the mean modulus determined at 0.59MPa is within the quoted range. As rubbers are essentially incompressible, the Poisson's ratio was assumed to be 0.49. A force of 50N applied to the central load pin was considered small enough to maintain the analysis within the experimental limits of proportionality.

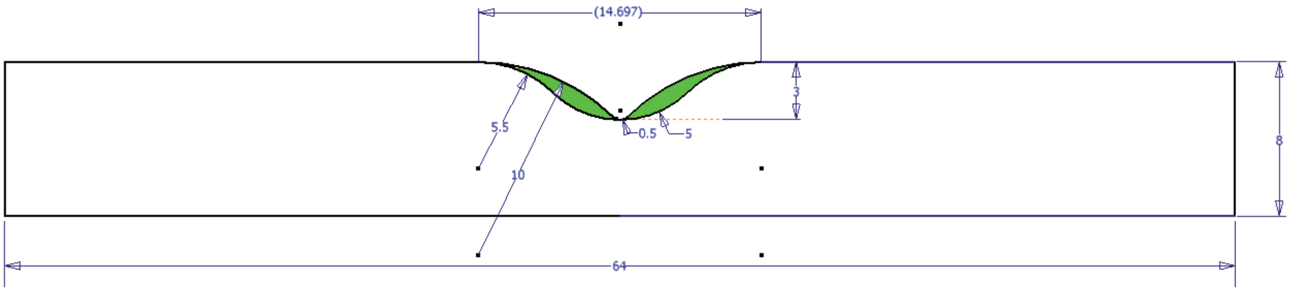

Figure 3. *Experimental model geometry*

In total, four scenarios were analysed: the control sharp notch, a blunt notch (i.e. without the 'fraenal plug'), the 'pseudo-filleted' notch and the un-notched beam (5mm in height). From values of maximum principal stress taken directly underneath the notch, stress concentration factors could be calculated and are provided in Table 1. One thing to note is how little impact the low modulus 'fraenal plug' has on the stress concentration (Table 1). In Figure 4 the localised effect of the control notch can be seen through a small region of red denoting high stress. Using the same stress contour scale, the 'pseudo-filleted' specimen in Figure 5 displays no such region and the 'fraenal plug' is effectively unstressed (blue).

Table 1. *Stress concentrations calculated via FEA*

	Tip Radius (mm)	$K_{t,\,FEA}$
Sharp 'Control' Notch	0.5	2.58
Blunt Notch	5.0	1.28
Blunt 'Pseudo-Filleted' Notch	5.0	1.28
Un-notched	N/A	1.00

Experimental

Two moulds were machined from aluminium and conformed to the blank dimensions of ISO 20795: 2008, with the exception of an increased depth of 8.5mm. Along the centreline of these moulds lay a recess of 2.5mm depth. This located pre-manufactured notch templates (sharp or blunt) that were produced from the same CAD geometry as used in the FEA studies. These templates were manufactured from high T_g polyphenylsulfone [PPSF] using a fused deposition modelling [FDM] machine (Stratasys Fortus 400 mc).

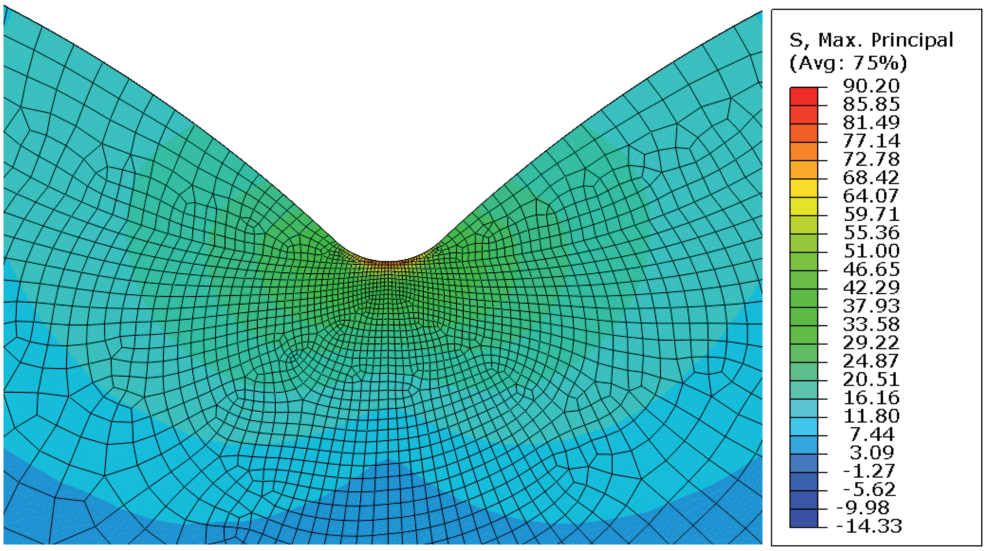

Figure 4. *Sharp control notch displaying a localised stress concentration at the notch (red). Scale bar in MPa*

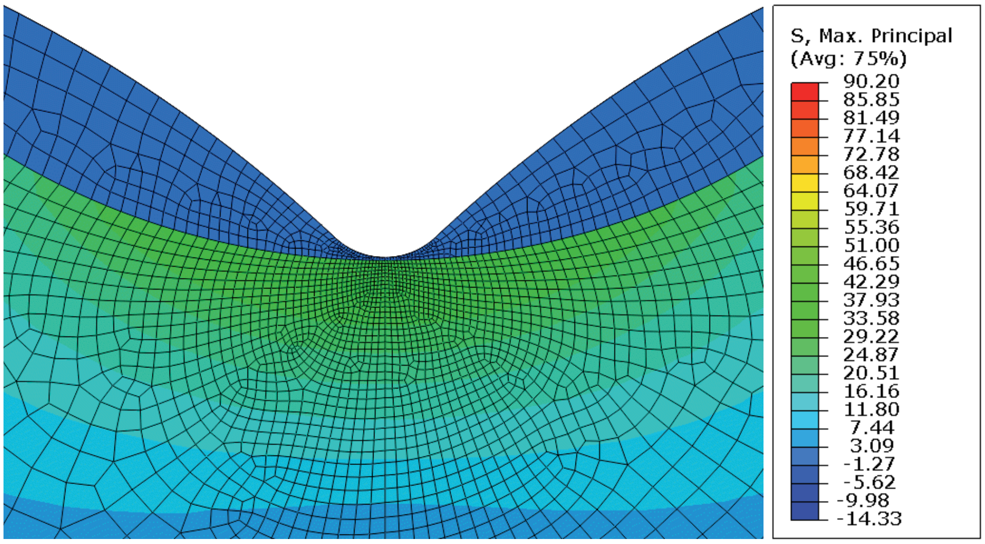

Figure 5. *'Pseudo-filleted' design shows relaxed stress concentration and effectively unstressed 'fraenal plug' (blue). Scale bar in MPa*

The bulk material of the specimens consisted of Minacryl Universal denture base acrylic resin, prepared according to manufacturer's instructions and cured in a water bath for 7 hours at 70°C. The fraenal mould inserts (sharp or blunt) were alternated between the two moulds, and the mould identity recorded with each resulting specimen, to ensure any deviation in notch depth from machining tolerances were compensated. After sectioning and polishing (P1200 SiC) the specimens were 8mm (±0.2) in height and 4mm (±0.2) in thickness.

The blunt notched specimens were then subjected to a second process to produce the 'pseudo-fillet'. Dentsply Eversoft produces a resin of honey-like consistency and was spread over the 'sharp' insert housed within the mould. Specimens were carefully placed into the mould ensuring alignment through use of spacers. Care was taken to ensure that the entire fraenal area had become occupied with soft liner. Post curing, the soft liner was carefully trimmed with a scalpel to lie flush with the global body. This required repeated refrigeration to firm the soft liner, without which it was too resilient to cut. A minimal re-polish was also undertaken without jeopardising specimen dimensions. The final specimens are presented in Figure 6 and Figure 7. The two-step mould process was successful in producing the sharp control notch centrally and tangentially within the 'fraenal plug'. This feature is difficult to distinguish and would not compromise the aesthetic properties of a complete denture.

Ten specimens of both control and 'pseudo-filleted' design were tested in wet conditions (50hrs ± 2hrs at 37 ± 1°C as per ISO 20795: 2008) on an Instron 1kN test machine at a cross-head displacement of 1mm/min. Testing itself was conducted under submerged conditions by circulating water (from the water bath used for pre-conditioning) through a sealed tank. In the absence of a more precise technique, alignment of the notch beneath the central load pin was done visually, with the aid of a drawn centreline.

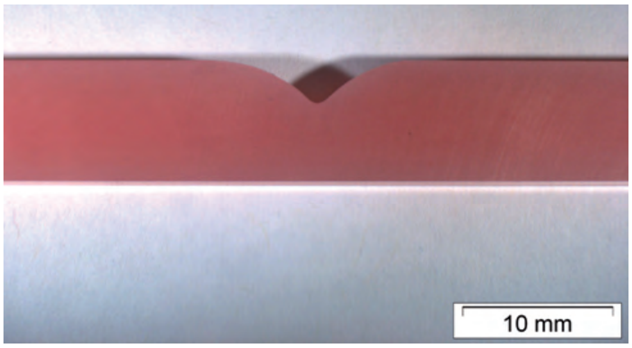

Figure 6. *Sharp control notch, entirely from denture base acrylic resin*

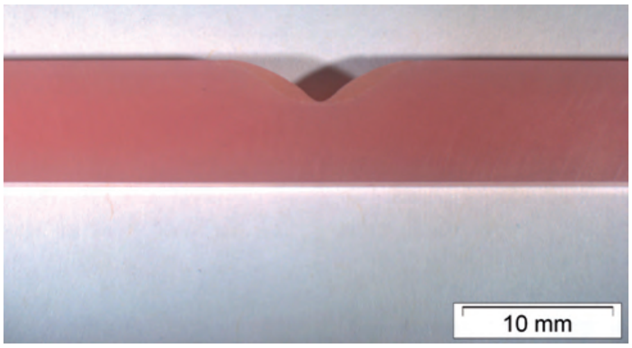

Figure 7. *'Pseudo-filleted' notch with 'fraenal plug' made from denture soft liner. The 'fraenal plug' is difficult to distinguish*

RESULTS

It is noted that results herein are for comparative purposes, being specific to the specimen design, and do not represent absolute material properties. To demonstrate the results, nominal flexural stress and strain were calculated using the cross-section beneath the notch (measured by optical microscopy). Dividing the ultimate flexural strength of Minacryl Universal (72.0MPa, based on additional flexural testing) by the nominal flexural stress at which the notched specimens failed should correlate to the predicted stress concentration factors. These experimentally determined factors are defined as the effective stress concentration factors (K_e).

From the stress-strain curves of the control 'sharp' specimens in Figure 8 it can be seen that the response was linear until rupture and, therefore, relatively brittle. The mean specimen failure stress was 56.1MPa ± 2.9MPa (SD), culminating in a K_e of 1.29 ± 0.07 (SD), and the mean total energy to failure (i.e. the area under the load-displacement curve) was 49.8mJ ± 5.8mJ (SD). In contrast, the 'pseudo-filleted' specimens displayed a more ductile response with deviation from linearity and a slight reduction in specimen stiffness (Figure 9). The mean specimen failure stress was 72.8MPa ± 4.2MPa (SD), culminating in a K_e of 0.99 ± 0.06 (SD), and the mean total energy to failure was 142.8mJ ± 42.0mJ (SD).

DISCUSSION

The effective stress concentration factors are significantly lower than those predicted. This is a common feature of plastics, where the material can sustain a stress level for some time prior to rupture, by plastically deforming. As the local stress at the notch tip approaches the yield stress, though strain may increase, the notch tip stress will remain constant and the stress state around the notch becomes uniform[6]. For the 'pseudo-filleted' design, the effective stress concentration is essentially unity and it can be concluded that denture base acrylic resin is insensitive to notches above a 5mm radius. The consequence of this material behaviour is that 'pseudo-filleting' of denture base acrylic resin does not offer the improvement in load to failure theory would suggest. Nonetheless, using a Student's *t*-test with a 95% confidence level, the interval between nominal failure stresses of the sharp control specimens and the 'pseudo-filleted' specimens is between 13.4 and 20.2MPa. As the range is solely positive, it can be stated that the 'pseudo-fillet' feature has provided a statistically significant improvement in specimen nominal failure strength[14]. When a material is notch insensitive, though increasing the notch radius may not significantly affect strength, it can still benefit by increasing the total energy to failure through a greater strain to failure[6]. This is apparent by observing the increased area underneath the stress-strain curves for the 'pseudo-filleted' specimens (Figure 9).

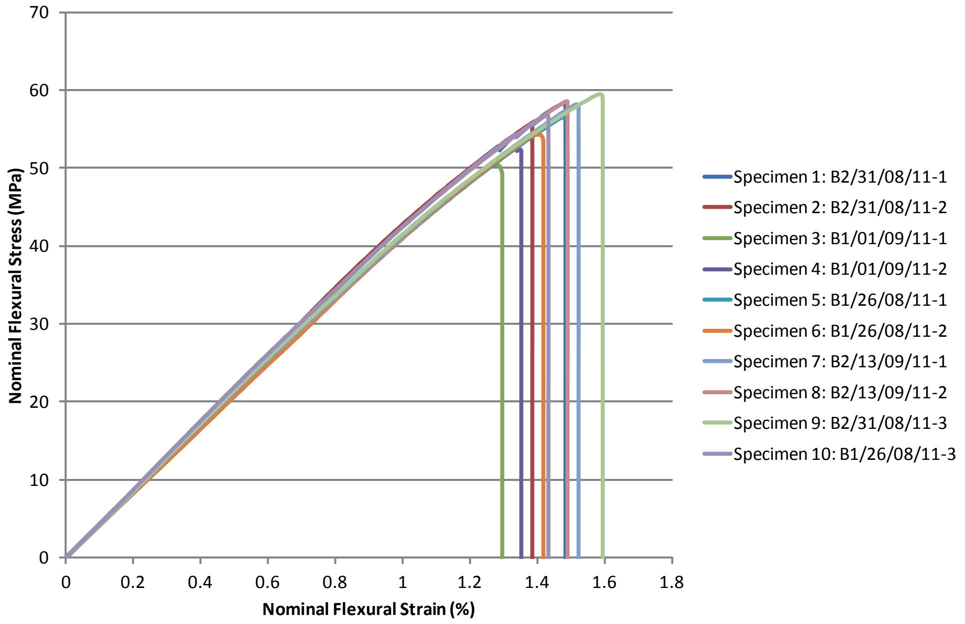

Figure 8. *Sharp control nominal flexural stress-strain*

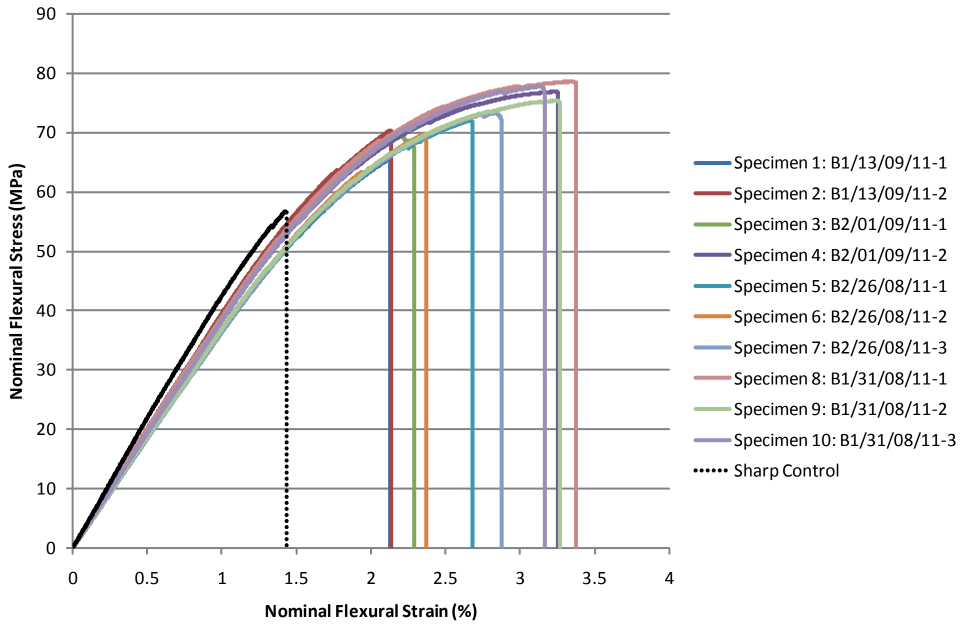

Figure 9. *'Pseudo-filleted' nominal flexural stress-strain with sharp control overlay*

The experimental procedure herein has demonstrated the advantages of a 'pseudo-filleted' design under static loading conditions, which is clinically relevant for the fracture of dentures due to impact and could result from dropping the denture or mishandling it during cleaning procedures. The other potential failure mechanism of dentures is fatigue, which has been shown by Kelly[5] to be exacerbated by the presence of stress concentrations. It is, therefore, reasonable to conclude that this design feature should also improve the fatigue life of a denture. The 'pseudo-fillet' is a simple, yet highly effective, design feature and should extend the service life of a typical complete denture. This would have likely ramifications on patient satisfaction, particularly if an *in vivo* failure could be avoided, and reduced costs derived from repair and replacement. However, this will only be valid if the durability of the soft 'franeal plug' is able to extend beyond the current service life of a denture. Dentsply Eversoft is a plasticised methacrylate soft liner and was chosen to create the 'fraenal plug' of the experimental specimens arbitrarily. The mechanical properties of these types of liners are generally unstable over time due to leaching of plasticisers[15] and cannot be recommended for use in 'pseudo-filleting'. Silicone based soft liners, on the other hand, have been shown to maintain their viscoelastic properties over 3 years of water immersion[16] and be unsusceptible to thermal cycling and mechanical brushing[17].

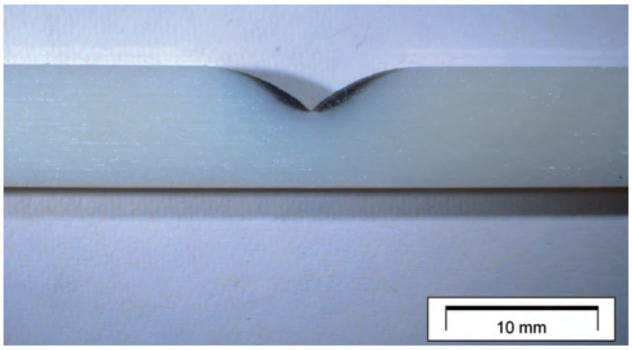

Figure 10. *'Pseudo-fillet' produced in one single process with the Objet Connex^{TM}*

In addition to the material properties of the 'fraenal plug', it is also imperative that a good bond with the denture is achieved and preserved to prevent microbial ingress[18]. While the bond strength of silicone based liners to denture base acrylic resin has been observed to reduce with water immersion[19,20], research into surface treatments offer potential improvement in adhesion. These include treatment to the surface of the denture base acrylic resin with maleic anhydride[21], lasers[22] and plasma[23]. Therefore, while further research into the durability of soft liners and their adhesive properties will be required, it is not believed this will be a limiting factor.

Within this study, the production of flexural specimens containing a 'pseudo-fillet' has been achieved using a simple two-step process with conventional denture base materials. It is believed this could be adapted to the current manufacturing process for complete dentures, but would be difficult and laborious for a dental technician and highly dependent on individual skill. The use of ALM (a.k.a. '3D printing') may provide an alternative manufacturing solution and has been proposed previously to produce complete dentures indirectly[24,25,26]. However, to create bespoke design features such as the 'pseudo-fillet', or the multi-material *palatal rugae* rib features proposed by White *et al*[27], would require using multi-material ALM to produce the denture directly.

Currently, the Objet Connex^{TM} is the only commercially available multi-material ALM machine and it has been used to reproduce an example of the 'pseudo-filleted' specimen (Figure 10). The bulk is made from rigid VeroWhite^{TM} and the flexible 'fraenal plug' from TangoBlack+^{TM}, both of which are acrylic based photopolymerising resins. The two resins can be co-blended to allow a grading of material properties across the interface. This is a beneficial feature that no other manufacturing process could provide and is often found in nature to reduce the likelihood of interfacial failure[28]. The example specimen shows that the 'pseudo-fillet' can be created directly using multi-material ALM in one single process and provides incentive for continued research into ALM and the direct production of complete dentures.

It can be postulated that the chemistry of these ALM resins are not too dissimilar to the acrylic based photopolymerising resins currently used in dentistry. Indeed, Inokoshi *et al.*[26] have used the same ALM process to create trial fitting dentures, from a medically approved variant, and deemed the dimensional accuracy of the technology acceptable for use. Additionally, the introduction of E-Dent 100 in the EnvisionTEC ALM process provides some capability for the direct manufacture of crowns and bridges. However, the development of a catalogue of biocompatible ALM materials, possessing suitable mechanical and thermal properties, as well as dimensional stability and colour variety, needs to be encouraged. Though the technology is not yet ready for mainstream use, achieving this will help realise the full potential of multi-material ALM in the production of complete dentures and, indeed, any medical implant geometrically constrained to patient anatomy. The technology offers not only a new method of producing prostheses, but a potential method of creating superior ones with the inclusion of 'pseudo-filleting' and other multi-material design features.

CONCLUSIONS

Through computational and experimental models, the concept of 'pseudo-filleting' has been shown to increase the specimen stress and strain to failure and, therefore, the total energy to failure, with only a modest sacrifice in stiffness. This would provide a significant improvement to the longevity of a complete maxillary denture and could lead to greater patient satisfaction and reduced overall cost. Practical execution on a complete denture could be difficult and time consuming using conventional manufacturing techniques and would be highly dependent on the individual skill of the dental technician. It is proposed that advances in ALM to produce dentures directly may provide a process capable of achieving 'pseudo-filleted' fraenal notches, *diastemas* and other such novel features in the future dental prosthesis.

ADDRESS FOR CORRESPONDENCE

Dr. James A.P. White, University of Bristol, Advanced Composites Centre for Innovation & Science (ACCIS), Department of Aerospace Engineering, Queen's Building, University Walk, Bristol, BS8 1TR. Email: J.White@bristol.ac.uk

REFERENCES

1. Carlsson G.E., Omar R. The Future of Complete Dentures in Oral Rehabilitation. A Critical Review. *J. Oral Rehabil.,* 2010; **37**: 143-156.
2. Bláhová Z., Neuman M. Physical Factors in Retention of Complete Dentures. *J. Prosthet. Dent.,* 1971; **25**: 230-235.
3. Jagger D.C., Harrison A., Jandt K.D. Review: The Reinforcement of Dentures. *J. Oral Rehabil.,* 1999; **26**: 185-194.
4. van Noort R. Introduction to Dental Materials. 3rd ed. Mosby Elsevier, 2008.
5. Kelly E. Fatigue Failure in Denture Base Polymers. *J. Prosthet. Dent.,* 1969; **21**: 257-266.
6. Pilkey W.D., Pilkey D.F. Peterson's Stress Concentration Factors. 3rd ed. John Wiley & Sons Inc, 2008.
7. Inglis C.E. Stresses in a Plate due to the Presence of Cracks and Sharp Corners. *Engineering* (*London*), 1913; **95**: 415.
8. Kolosoff G. Dissertation, *St. Petersburg, Russia*, 1910.
9. Kibi M., Ono T., Dong J., Mitta K., Gonda T., Maeda Y. Development of an RPD CAD System with Finite Element Stress Analysis. *J. Oral Rehabil.,* 2009; **36**: 442-450.
10. Ateş M., ilingir A., Sülün T., Sünbüloğlu E., Bozdağ E. The Effect of Occlusal Contact Localization on the Stress Distribution in Complete Maxillary Denture. *J. Oral Rehabil.,* 2006; **33**: 509-513.

11. Ellis B., Lamb D.J., Al-Nakash S. The Elastic Modulus of Soft Denture Liners. *J. Biomed. Mater. Res., 1980*; **14**: 731-742.
12. Sato Y., Abe Y., Okane H., Tsuga K. Finite Element Analysis of Stress Relaxation in Soft Denture Liner. *J. Oral Rehabil.,* 2000; **27**: 660-663.
13. Wilson H.J., Tomlin H.R. Soft Lining Materials: Some Relevant Properties and their Determination. *J. Prosthet. Dent.,* 1969; **21**: 244-250.
14. Rees D.G. Essential Statistics. Chapman & Hall/CRC, 2001.
15. Mese A., Guzel K.G. Effect of Storage Duration on the Hardness and Tensile Bond Strength of Silicone and Acrylic Resin-Based Resilient Denture Liners to a Processed Denture Base Acrylic Resin. *J. Prosthet. Dent.*, 2008; **99**: 153-159.
16. Murata H., Taguchi N., Hamada T., McCabe J.F. Dynamic Viscoelastic Properties and the Age Changes of Long-Term Soft Denture Liners. *Biomaterials*, 2000; **21**: 1421-1427.
17. Hermann C., Mesquita M.F., Consani R.L.X., Henriques G.E.P. The Effect of Aging by Thermal Cycling and Mechanical Brushing on Resilient Denture Liner Hardness and Roughness. *J. Prosthodont.*, 2008; **17**: 318-322.
18. Jacobsen N.L., Mitchell D.L., Johnson D.L., Holt R.A. Lased and Sandblasted Denture Base Surface Preparations Affecting Resilient Liner Bonding. *J. Prosthet. Dent.*, 1997; **78**: 153-158.
19. Al-Athel M., Jagger R., Jagger D. Effect of Ageing on the Bond Strength of a Permanent Denture Soft Lining Material. *J. Oral Rehabil.*, 2002; **29**: 992-996.
20. Amin W.M., Fletcher A.M., Ritchie G.M. The Nature of the Interface between Polymethyl Methacrylate Denture Base Materials and Soft Lining Materials. *J. Dent.*, 1981; **9**: 336-346
21. Turgut M., Bolayir G., Dogan O.M., Keskin S., Dogan A., Boztug A. Bond Strength of a Silicone Soft Lining Material to Poly(methyl methacrylate) Resin Treated with Maleic Anhydride and its Terpolymers. *J. Adhesion*, 2007; **83**: 927-938.
22. Soygun K., Bolayir G., Dogan A., Demir H., Dogan O.M., Keskin S. The Effect of Surface Treatments on Tensile Bond Strength between a Silicone Soft Liner and a Heat-Cured Denture Base Resin. *J. Adhesion*, 2011; **87**: 951-965.
23. Bicer A.Z.Y., Dogan A., Keskin S., Dogan O.M. Effect of Argon Plasma Pretreatment on Tensile Bond Strength of a Silicone Soft Liner to Denture Base Polymers. *J. Adhesion*, 2013; **89**: 594-610.
24. Maeda Y., Minoura M., Tsutsumi S., Okada M., Nokubi T. A CAD/CAM System for Removable Denture. Part 1: Fabrication of Complete Dentures. *Int. J. Prosthodont.,* 1994; **7**: 17-21.
25. Sun Y., Lü P., Wang Y. Study on CAD & RP for Removable Complete Dentures. *Comp. Meth. Prog. Biomed.,* 2009; **93**: 266-272.
26. Inokoshi M., Kanazawa M., Minakuchi S. Evaluation of a Complete Denture Trial Method Applying Rapid Prototyping. *Dent. Mater. J.,* 2012; **31**:40-46.
27. White J.A.P., Bond I.P., Jagger D.C. Improving Mechanical Properties of Maxillary Complete Dentures Through a Bioinspired Engineering Design. *Int. J. Prosthodont.,* 2011; **24**: 589-598.
28. Waite J.H., Vaccaro E., Sun C., Lucas J.M. Elastomeric Gradients: A Hedge Against Stress Concentration in Marine Holdfasts?. *Philos. T. R. Soc. B.,* 2002; **357**: 143-153.