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DIGITAL IMAGE CORRELATION ANALYSIS OF THE BOND STRENGTH BETWEEN PRE-FABRICATED ACRYLIC TEETH AND DENTURE BASE RESIN UNDER SIMULATED LOAD CONDITIONS

KORELACIJA DIGITALNIH SLIKA U ANALIZI ČVRSTOĆE VEZE FABRIČKIH AKRILATNIH ZUBA I BAZE U USLOVIMA SIMULACIJA OPTEREĆENJA

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Keywords
- Digital Image Correlation (DIC)
- dental bonding
- acrylic resins
- load angle
- dental prosthesis, removable

Abstract

This study aims to investigate biomechanical behaviour of the bond between prefabricated acrylic teeth and heat-polymerised denture base resin under different loading angles, using 2D Digital Image Correlation method (2D DIC), a method that enables real-time, full-field analysis of displacement and deformation field. The experimental setup involves samples loaded at 45° and 90°, representing clinically relevant angulations that simulate forces encountered during mastication. A two-part positioning tool is developed via 3D printing to guarantee uniform samples positioning. Stochastic pattern is applied to each sample to enable 2D DIC method tracking. 2D DIC enables visualisation of displacement and von Mises strain fields, particularly in the critical regions of the tooth-resin interface. The results show differences in force, deformation, and displacement between samples angle loaded both at 90° and 45°. That suggests significant impact of loading angle and contact area between tooth and denture base.

Ključne reči
- digitalna korelacija slike (DIC)
- adhezija u stomatologiji
- akrilatne smole
- ugao opterećenja
- mobilne stomatološke nadoknade

Izvod

Cilj ove studije je da se analizira biomehaničko ponašanje veze između fabričkih akrilatnih zuba i baze proteze izrađene od toplopolimerizujućeg akrilata, pri različitim uglovima opterećenja, korišćenjem metode digitalne korelacije slike (DIC), koja omogućava detaljno praćenje deformacija i pomeranja u realnom vremenu. Eksperimentalni protokol uključuje opterećenje uzoraka pod uglovima od 45° i 90°, koji predstavljaju klinički relevantne pravce delovanja sila tokom žvakanja. Radi postizanja uniformnosti oblika i položaja uzoraka, razvijen je dvodelni nosač izrađen 3D štampom. Površina svakog uzorka je prekrivena stohastičkom šarom kako bi se obezbedilo precizno praćenje deformacija tokom DIC analize. Primena DIC metode omogućuje vizuelizaciju raspodele napona i polja pomeranja, naročito u kritičnim zonama na spoju zub-baza. Rezultati pokazuju razliku u sili, deformaciji i pomeranju između uzoraka koji su opterećeni pod uglom od 90° i 45°. To ukazuje na značajan uticaj ugla opterećenja na ponašanje materijala.

INTRODUCTION

Tooth loss affects patient functionality, aesthetics, and quality of life. Removable dentures still remain a key treatment option, particularly when implant placement is not feasible. One of the main issues for denture longevity is the bond strength between artificial acrylic teeth and the acrylic denture base /1, 2/. Weak bonding can lead to the loss of the artificial tooth, reduced function and need for repair, /3/.

Traditional testing methods, such as shear tests, do not enable precise analysis of bond features in this matter /4, 5/. Shear test limitation is its inability of capturing progressive changes that occur within the bonded interface before fracture. Also, test limitation contributes not noticing micro deformations, stress concentrations or development of fracture zones. In contrast, the method of Digital Image Correlation (DIC) allows real-time mapping areas of displacement and deformation and also provides its visualisation /6/. DIC offers insight into localised critical zones providing prediction of fracture points /7/. In addition, DIC method has been increasingly used in biomedical material research due to its ability to identify deformation and critical fracture zones /8/. In this study, a combination of shear bond test and DIC method is applied. In order to gain a complete insight of mechanical behaviour of the contact areas between artificial acrylic teeth and denture acrylic base, this study involves identification of critical zones of possible deformation which could lead to fractures. DIC enables reliable monitoring and displacements identification of loaded and deformed samples, respectively /9/. This corresponds with modern experimental protocols which include qualitative insights into contact areas of artificial acrylic teeth and acrylic dental base. DIC emphasizes possibility of advanced measurement techniques, /10/.

The aim of this study is to examine the applicability of 2D DIC method for analysing the bond strength between artificial acrylic teeth and acrylic denture base subjected to loading under angles of 45° and 90° and to show the mechanical loading behaviour of contact areas.

MATERIALS AND METHODS

The study was conducted in collaboration between the Clinic for Prosthodontics of the School of Dental Medicine, University of Belgrade and the Optical Measurement Centre of the Faculty of Mechanical Engineering, University of Belgrade. The sample materials for preparation included prefabricated acrylic teeth (Ivoclar SR Vivodent, Liechtenstein) and heat-polymerised acrylic denture base resin (Ivoclar Triplex Hot, Liechtenstein). The samples were prepared in dental laboratory by standardised flasking technique /11/. In order to exert this experiment, a two-part Positioning Tool (PT) is designed. The PT accurately places prefabricated acrylic teeth within the acrylic denture base during sample preparation, prior to the flasking process. The two-part PT tool is fabricated via 3D printer (Bambu Lab X-1 Carbon, China) by PETG material. Figure 1 shows PT tool design: a) 3D model of PT tool; and b) 3D Printed PT tool. The lower part of the PT tool has a purpose in placing the acrylic denture base, /12/. The PT tool upper part overlaps the lower part as a lid. The lid has a hole used for more easier and precise teeth denture base positioning. A total of six samples were fabricated. Each sample consists of a prefabricated acrylic right upper central incisor embedded in heat-polymerised acrylic denture base. The right upper central incisor is selected due to its prominent and anatomically central position within dental arch, /13/. In the position of central occlusion of lower jaw, the occlusal angle is formed between the upper central and lower central incisor, approximately 45°. Its functional and aesthetic significance frequently makes this tooth as a fitting place for debonding of the acrylic denture base.

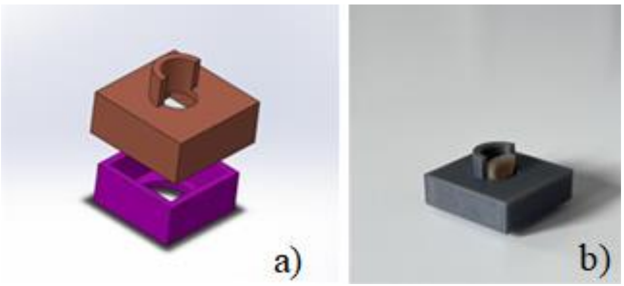

Figure 1. Design of a two-part Positioning Tool (PT) for uniform test specimen positions: a) 3D model of PT; b) 3D printed PT.

All samples (n = 6) are divided into two groups of three each, representing load angles of 45° (Group 1) and 90° (Group 2). All sample surfaces are prepared by applying a stochastic pattern in the imaging area of the 2D DIC camera. The stochastic pattern is made by applying a white matte base coat with a fine black speckled coat. This provides optimal contrast for 2D DIC analysis /14/. Figure 2 shows all specimens with a finished stochastic pattern.

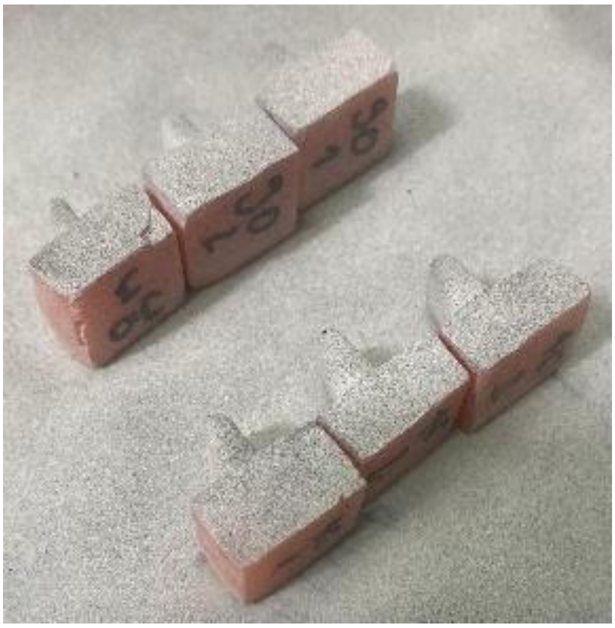

Figure 2. Stochastic pattern.

The experimental setup consists of a camera for the DIC method, a testing machine, and a fixture mounted on it for securing and defining the sample angle during loading, as shown in Fig. 3. One camera (Basler, Germany) with 2 MP resolution is used for the 2D DIC method. GOM Correlate software enables both precise measuring of displacements of samples section line in the vertical direction and sample deformations. The camera is placed laterally in relation to the samples to record the behaviour of the contact area (contact place between prefabricated acrylic tooth and acrylic denture base) during the loading procedure at a distance of 30 cm from the samples. The bond strength is tested using a Shimadzu AGS-X universal testing machine at a loading speed of 1 mm/min. The fixture for securing and defining the angle consists of a clamp (used to fix the sample) and an arc slider which allows the sample to be positioned at multiple angles.

Figure 3. Experimental setup.

RESULTS AND DISCUSSION

The GOM Correlate software is used to analyse displacement and the von Mises strain field in the samples, /8/.

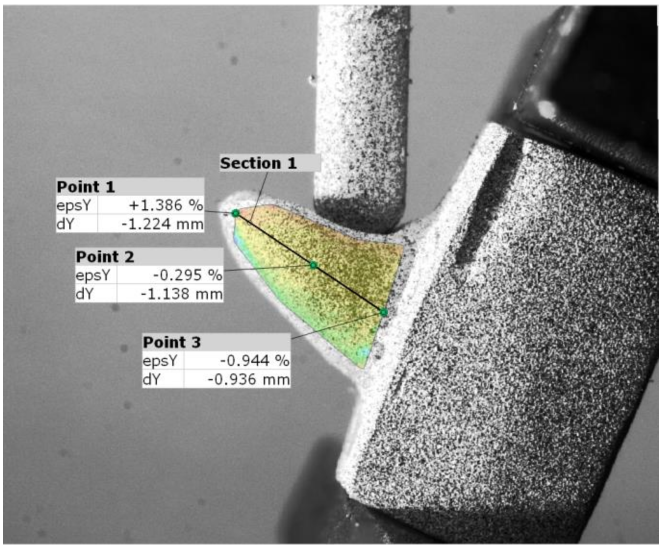

Figure 4. Visualisation of the von Mises strain field with measuring elements.

The displacement of samples in the vertical direction is analysed by measuring Section 1 and Points 1, 2 and 3. Section 1 is aligned with the tooth axis. Point 1 is located at the beginning of Section 1, Point 2 at the middle, and Point 3 at the end of Section 1 (tooth base).

These results confirm that the angle of loading has a major impact on the contact area between artificial acrylic tooth and acrylic denture base.

Average values with standard deviation (SD) per group and p-values (Mann-Whitney test) are presented in Table 1. Statistical analyses are performed to show the differences between experimental groups and the correlation between fracture force, deformation and displacement. The Mann-Whitney test is used to compare fracture force, deformation, and displacement between Group 1 and Group 2, because there is not a normal distribution of the data and it is suitable for a small amount of samples, /15/.

Table 1. Average values ±SD per group and p-value (Mann–Whitney test).

Parameter	Group 1 (n = 3)	Group 2 (n = 3)	p-value (Mann-Whitney)
Avg. force (N)	420.19±8.56	134.74±61.01	0.050
Avg. deformation (%)	-1.28±0.09	-0.51±0.08	0.050
Avg. displacement (mm)	0.18±0.03	0.07±0.004	0.050

The results show that Group 1 demonstrates greater fracture force, deformation, and displacement compared to the Group 2, indicating that load angle has a main biomechanical effect.

Spearman's correlation test is used to assess the relationship between fracture force, deformation and displacement, providing insight into how these parameters are interrelated /16/. Correlation coefficients *r* and p-values are presented in Table 2.

Table 2. Spearman correlation between variables.

Correlations	Spearman *r*	p-value
Avg. force ↔ Avg. deformation	-0.771	0.072
Avg. force ↔ Avg. displacement	+0.771	0.072
Avg. deformation ↔ displacement	-0.714	0.111

Although the Mann-Whitney p-values are at the threshold of significance ($p = 0.050$), the large effect size ($r = 0.80$) suggests a strong influence of load angle even with a small amount of samples. Spearman's correlation reveals that the applied force positively correlates with displacement and negatively relates with deformation. This indicates that vertical movement does not directly predict percentage strain, and that these parameters reflect different biomechanical aspects of contact area between artificial acrylic tooth and acrylic denture base under loading.

CONCLUSION

The present study demonstrates that the angle of loading significantly affects the contact area between prefabricated acrylic tooth and acrylic denture base. Angled loading at 45° results in higher fracture forces, greater deformation, and increased vertical displacement compared to vertical loading at 90°, due to a more complex stress distribution. Displacement and deformation reflect different biomechanical aspects. Deformation is concentrated near the incisal region, while maximal strain is observed in lower regions of the samples. The application of 2D Digital Image Correlation (DIC) enables precise, localised measurement of displacement and strain fields, providing new insight into the contact area between prefabricated acrylic tooth and acrylic denture base /17-19/. In this study, even though no surface pre-treatment is applied, literature suggests that techniques such as MMA monomer application, alumina sandblasting, or other chemical treatments can significantly improve bonding performance by altering surface energy and roughness /20/. Recent research emphasises the benefit of integrating DIC with finite element analysis (FEA), which allows both experimental validation and predictive modelling of contact areas exposed to occlusal stress in denture components /8/. This combines approaches that enhances the identification of high-risk occlusal contact areas. Clinically, these findings underline the necessity of evaluating potential tangential forces and their impact of weakening the bonded contact area of denture parts over time /3/. Findings obtained in this study can be advisable for dental laboratories in denture design, such as use of additional mechanical and chemical retention or targeted contact area preparation in optimising denture durability.

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REFERENCES

1. Pavlin, M., Gubeljak, N., Predan, J., Ćelić, R. (2024), *Evaluation of the bond strength between the acrylic teeth and reinforced or non-reinforced complete denture base*, Acta Stomatol. Croat. 58(3): 218-232. doi: 10.15644/asc58/3/3

2. Madhav, G.V., Raj, S., Yadav, N., et al. (2013), *Shear bond strength of acrylic teeth to acrylic denture base after different surface conditioning methods*, J Contemp. Dent. Pract. 14(5): 892-897. doi: 10.5005/jp-journals-10024-1422
3. Radford, D.R., Juszczyk, A.S., Clark, R.K.F. (2014), *The bond between acrylic resin denture teeth and the denture base: recommendations for best practice*, Br. Dent. J, 216(4): 165-167. doi: 10.1038/sj.bdj.2014.99
4. Van Meerbeek, B., Peumans, M., Poitevin, A., et al. (2010), *Relationship between bond-strength tests and clinical outcomes*, Dent. Mater. 26(2): e100-e121. doi: 10.1016/j.dental.2009.11.148
5. El Mourad, A.M. (2018), *Assessment of bonding effectiveness of adhesive materials to tooth structure using bond strength test methods: A review of literature*, Open Dent. J, 28(12): 664-678. doi: 10.2174/1745017901814010664
6. Aranđelović, M., Petrović, A., Sedmak, S. (2024), *Digital image correlation application to structural integrity assessment*, Struct. Integr. Life, 24(1): 87-91. doi: 10.69644/ivk-2024-01-0087
7. Trajković, I., Balać, M., Milošević, M., Međo, B. (2025), *Application of the DIC method in determining fracture mechanics parameters on ring-shaped specimens with a sharp notch manufactured using the FDM technique*, Struct. Integr. Life, 25(1): 127-133. doi: 10.69644/ivk-2025-01-0127
8. Yoon, S., Jung, H.-J., Knowles, J.C., Lee, H.-H. (2021), *Digital image correlation in dental materials and related research: A review*, Dent. Mater. 37(5): 758-771. doi: 10.1016/j.dental.2021.02.024
9. Alhamdan, M.M., Knowles, J.C., McDonald, A. (2019), *Digital image correlation and strain gauges to map and compare strain in teeth with different quantity and quality of remaining tooth structure*, Int. J Prosthodont. 32(1): 82-90. doi: 10.11607/ijp.6044
10. Messias, A., Neto, M.A., Piedade, A.P., et al. (2025), *Comparison of surface strains of polymeric frameworks for fixed implant-supported prostheses: A digital image correlation study*, Materials, 18(8): 1700. doi: 10.3390/ma18081700
11. Negreiros, W.A., Consani, R.L.X., Mesquita, M.F., et al. (2009), *Effect of flask closure method and post-pressing time on the displacement of maxillary denture teeth*, Open Dent. J, 3: 21-25. doi: 10.2174/1874210600903010021
12. Mitrović, N., Golubović, Z., Mitrović, A., et al. (2024), *Influence of aging on the flexural strength of PLA and PLA-X 3D-printed materials*, Micromachines, 15(3): 395. doi: 10.3390/mi15030395
13. Zuckerman, G.R. (2003), *A reliable method for securing anterior denture teeth in denture bases*, J Prosthet. Dent. 89(6): 603-607. doi: 10.1016/s0022-3913(02)52713-x
14. Mitrović, N., Mitrović, A., Travica, M. (2023), *Tensile testing of flat thin specimens using the two-dimensional digital image correlation method*, Struct. Integr. Life, 23(1): 9-13.
15. Ghasemi, A., Zahediasl, S. (2012), *Normality tests for statistical analysis: a guide for non-statisticians*, Int. J Endocrinol. Metab. 10(2): 486-489. doi: 10.5812/ijem.3505
16. Mukaka, M.M. (2012), *Statistics corner: A guide to appropriate use of correlation coefficient in medical research*, Malawi Med. J, 24(3): 69-71.
17. Sawamura, M., Nakano, H., Shiogama, M., et al. (2023), *Using digital image correlation to measure displacement and strain during involving distal movement of anterior teeth with clear aligner*, Dent. Mater. J, 42(4): 493-500. doi: 10.4012/dmj.2022-255
18. Milosevic, N., Younise, B., Sedmak, A., et al. (2021), *Evaluation of true stress-strain diagrams for welded joints by application of Digital Image Correlation*, Eng. Fail. Anal. 128: 105609. doi: 10.1016/j.engfailanal.2021.105609
19. Jelić, A., Sekulić, M., Travica, M., et al. (2022), *Determination of mechanical properties of epoxy composite materials reinforced with silicate nanofillers using digital image correlation (DIC)*, Polymers, 14(6): 1255. doi: 10.3390/polym14061255
20. Chaudhuri, N.G., Lahiri, B., Francis, N.T., et al. (2024), *Evaluation of the bond strength of acrylic teeth to denture base after various chemical surface treatments: An in vitro study*, J Contemp. Dent. Pract. 25(6): 514-517. doi: 10.5005/jp-journals-10024-3670