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# Shear bond strength vs interfacial fracture toughness — Adherence to CAD/CAM blocks

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## ARTICLE INFO

### Article history:

Received 13 June 2019

Received in revised form

10 October 2019

Accepted 11 October 2019

### Keywords:

Dental materials

Dental bonding

Fracture mechanics

CAD/CAM

Composite resins

Dental cements

## ABSTRACT

**Objective.** To compare shear bond strength (SBS) and interfacial fracture toughness ( $IK_{IC}$ ) results when assessing the effect of surface roughness and thermocycling on the adherence of a resin composite luting agent (RCLA) to a CAD/CAM resin composite block (RCB).

**Methods.** Tetric CAD HT along with the recommended bonding system, Adhese Universal and Variolink Esthetic LC, were used. Surface roughness was achieved with 600/320/60 grit SiC papers. Samples were stored 24 h in 37 °C water or thermocycled 10000 × (5 °C–55 °C) prior to testing. Results were analyzed by univariate ANOVA and Scheffé modified t-tests ( $\alpha = 0.05$ ). Fractured specimens were viewed with a stereo microscope and selected specimens with a scanning electron microscope.

**Results.** SBS results showed a significant difference between the 60 grit group and the other groups, both after 24 h and thermocycling. A large number of SBS samples showed cohesive fracture or subsurface damage in RCB. Thermocycling led to a significant decrease in SBS in all groups.  $IK_{IC}$  results showed no significant differences due to surface preparation after 24 h storage in 37 °C. After thermocycling, there was a significant difference between the 60 and the 600 grit groups. All  $K_{IC}$  samples fractured adhesively at the RCB surface.  $K_{IC}$  of the RCLA was significantly higher than  $IK_{IC}$  of all groups.

**Significance.** The results endorse the use of fracture mechanics methodology for the assessment and characterization of adherence, while identifying difficulties in its implementation. The results suggest also that adherence to CAD/CAM RCB may be limited by the strength of the resin composite block — adhesive interface.

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## 1. Introduction

In dental research, the assessment of adherence is almost exclusively achieved via bond strength tests [1], tests that have major shortcomings [2–5]. A fracture mechanics approach may enable a more accurate assessment of adherence and an

unambiguous identification of the weakest interface or component in an adhesive interface [1,6]. There is a scarcity of evidence regarding a comparison between the two methodologies, i.e. bond strength tests vs fracture mechanics tests, in the characterization of dental adhesive interfaces [7].

Over the last several years, there has been a continuous increase in the use of computer-aided design/computer-aided

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<https://doi.org/10.1016/j.dental.2019.10.003>

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manufacturing (CAD/CAM) resin composite blocks (RCB) for indirect restorations [8,9]. Among the purported advantages of using RCB are the ease of manufacturing and intra-oral reparability. From an adhesive point of view, adherence to RCB is challenging since, due to the high degree of conversion achieved during fabrication [10], there is little likelihood to obtain any significant chemical bonding. Bonding, therefore, relies mainly on mechanical interlocking to the roughened surface of the CAD/CAM produced restorations, roughness that could be further enhanced by different preconditioning procedures, such as sandblasting and/or acid etching [11]. There is a scarcity of evidence regarding the effect of surface roughness on the adherence to RCB.

Based on the above briefly exposed rationale, two research questions were identified:

- 1 Which test method, shear bond strength (SBS) or interfacial fracture toughness ( $IK_{IC}$ ), could provide more meaningful insights into the adherence between CAD/CAM RCB and resin composite luting agent (RCLA)?
- 2 Does surface roughness influence SBS and  $IK_{IC}$  between CAD/CAM RCB and RCLA?

Moreover, considering the significant impact that storage in water can have on both material properties and on adhesive interfaces, a third research question became relevant, i.e.:

- 3 Does thermocycling (10,000 cycles) influence SBS and  $IK_{IC}$  between CAD/CAM RCB and RCLA?

The aim of this study, therefore, was to compare the two test methodologies, SBS and  $IK_{IC}$ , and to assess the effect of surface roughness and thermocycling on SBS and  $IK_{IC}$  of CAD/CAM RCB – RCLA adhesive interfaces by testing the following three null hypotheses: (1) there is no difference between the information provided by SBS or  $IK_{IC}$  tests with regards to the adherence between CAD/CAM RCB – RCLA; (2) surface roughness does not affect SBS and  $IK_{IC}$  of CAD/CAM RCB – RCLA; and (3) 10,000 thermocycles do not affect SBS and  $IK_{IC}$  of CAD/CAM RCB – RCLA adhesive interfaces.

## 2. Materials and methods

Three grit size SiC papers were selected for this study (ANSI 600, 320 and 60) in order to achieve surface roughness corresponding to the most commonly used surface roughness in bond strength tests (600 grit) [1], to the surface roughness achieved with a carbide bur (320 grit) [12], and to the maximum surface roughness achieved with dental burs and sandblasting (60 grit).

Tetric CAD HT A3 (Ivoclar Vivadent, Schaan, Lichtenstein; LOT W93631, expiry 2020), a newly released high translucency CAD/CAM RCB, along with the manufacturer recommended bonding system, comprised of Adhese Universal (LOT X31764, expiry 2020) in combination with the RCLA Variolink Esthetic LC (LOT X24209, expiry 2020), were selected for this study. For consistency, the light curing unit used was Bluephase Style [(1313.60 ± 11.41) mW/cm<sup>2</sup>; irradiance was monitored with a NIST-referenced USB4000 Spectrometer (Ocean Optics;

FL, USA)], by the same manufacturer. An Isomet (Buehler, IL, USA) low speed saw, a LECO SS-200 (LECO Corp. MI, USA) grinding/polishing machine and a LECO VC 50 saw, all operated under constant water irrigation, were also used.

For SBS, 120 (5.9 × 5.9 × 6.9) mm sections were obtained by sectioning ten CAD/CAM RCB into 12 cuboids. Using double-sided tape, each section was placed on a Mylar strip, an embedding metal cylinder (h = 19 mm,  $\Phi$  = 19 mm) was centered above it and was then half-filled with Technovit 4004 (Hareus Kultzer GmbH, Wehrheim, Germany), a methacrylate embedding material. For bonding, the surface of the embedded CAD/CAM RCB section was preconditioned with the selected SiC grit, followed by thorough rinsing with water and air-drying. The bonding agent was then applied and constantly rubbed onto the surface for 20 s. The adhesive was then air-dried gently and light cured for 10 s. A plastic lid, carrying a light-body polyvinyl silicone half-split insert with a centered cylindrical opening (h = 4 mm and  $\Phi$  = 3 mm), was centered on top of the specimen; Variolink Esthetic LC was syringed into the cylindrical opening and light-cured for 20 s. After careful removal of the lid, the RCLA was further cured for 20 s and the specimen was then immersed in 37 °C water. For SBS determination, the protocol outlined in ISO/TS 11405:2015 – Dentistry – Testing of adhesion to tooth structure was followed. The embedded specimens were secured in a Zwick universal testing machine (Zwick, Germany) and a chisel was brought into contact with the adhesive interface, ensuring proximity to the interface and axial alignment. The test was conducted with a cross-head speed of 1 mm/min. The maximum load at fracture ( $F_{max}$ , in N) and the contact surface area (A, 7.07 mm<sup>2</sup>) were used to calculate SBS, in MPa, using the formula below:

$$SBS = \frac{F_{max}}{A}$$

For  $IK_{IC}$ , ten CAD/CAM RCB were sectioned into six sections and each section was ground, using a custom made grinding jig, into a triangular prism [(6 × 6 × 6 × 12) mm] that was further sectioned into two; thus, 120 specimens were obtained. For preconditioning and to ensure correct alignment, each specimen was clamped into the mobile arm of the LECO VC 50 and brought in contact with the selected SiC paper that was attached to the surface of a cutting blade. The ground surface was rinsed with water and air-dried. The specimen was placed in a split Teflon mould, with the ground surface slightly protruding. The bonding agent was applied and constantly rubbed onto the surface for 20 s. This was followed by gentle air-drying and 10 s light curing. The specimen was then fully inserted in the mould, the mould was filled with RCLA, which was light-cured for 20 s. Post-cure of 20 s was performed after careful removal from the mould. The bonded specimen was then immersed in 37 °C water. For  $IK_{IC}$  determination, the bonded specimen was secured in one half of the specimen holder, a small defect was introduced into the adhesive interface with a surgical blade (Ted Pella, USA) and the specimen was then secured into the second half of the specimen holder, using the mounting block. The test assembly was then loaded in tension at a cross-head speed of 0.1 mm/min. The maxi-

**Table 1 – Results (Mean ± SD) of (interfacial) fracture toughness ( $IK_{IC}$ ) and shear bond strength (SBS) tests along with the results of statistical\* analysis.**

Test	$K_{IC}$ (in MPa m <sup>1/2</sup> )**		SBS (in MPa)***	
	24 h	Thermocycled	24 h	Thermocycled
600	0.85 ± 0.31 <sup>A a</sup> (n = 12/20)	0.37 ± 0.15 <sup>B a</sup> (n = 16/20)	16.86 ± 4.89 <sup>A a</sup> (n = 20)	10.11 ± 3.04 <sup>B a</sup> (n = 20)
320	0.89 ± 0.17 <sup>A a</sup> (n = 17/20)	0.59 ± 0.15 <sup>B ab</sup> (n = 10/20)	17.92 ± 5.84 <sup>A a</sup> (8/20 CB)	7.71 ± 3.99 <sup>B a</sup> (3/20 SSD)
60	0.96 ± 0.23 <sup>A a</sup> (n = 18/20)	0.64 ± 0.31 <sup>B b</sup> (n = 15/20)	27.77 ± 8.87 <sup>A b</sup> (17/20 CB)	16.91 ± 3.62 <sup>B b</sup> (20/20 SSD)
Variolink Esthetic LC	1.62 ± 0.22 <sup>A b</sup> (n = 15/20)	1.11 ± 0.21 <sup>B c</sup> (n = 20/20)	NA	NA

\* Uppercase superscript letters refer to within row comparisons, while lowercase superscript letters refer to within column comparisons. Identical letters identify groups that are not statistically significantly different (One-way ANOVA followed by Scheffé test, at  $\alpha = 0.05$ ).

\*\* The number of specimens prepared and tested for each group was 20. However, for certain groups, the number of valid results (n) was lower, as indicated (see text as well). Only valid results were used in calculations.

\*\*\* The number of specimens prepared and tested for each group was 20. CB stands for cohesive fracture in resin composite block and SSD stands for subsurface damage (see text). All 20 values were used in calculations.

mum load at crack arrest or fracture ( $F_{max}$ , in N) was used to calculate  $K_{IC}$ , in MPa·m<sup>1/2</sup>, using the equation below:

$$K_{IC} = Y_{min}^* \frac{F_{max}}{D\sqrt{W}}$$

where  $Y_{min}^* = 28$ ,  $D = 12$  mm and  $W = 10.4$  mm [13].

A Teflon mould was used to obtain (6 × 6 × 6 × 12) mm triangular prisms of Variolink Esthetic LC RCLA for  $K_{IC}$  determination, conducted as described above. The samples were stored in water at 37 °C.

Following the experimental design, SBS,  $K_{IC}$  and  $IK_{IC}$  were determined after 24 h storage in water at 37 °C and after additional 10,000 thermocycles between 5 °C and 55 °C, with a dwell time of 30 s in each and 10 s in-between [14].

Each group had 20 specimens to enable the detection of a standardized difference of 2, with a power of 80 %, at a confidence level of 95 % [15]. The results of SBS,  $K_{IC}$  and  $IK_{IC}$  tests were statistically analyzed using univariate ANOVA (for surface roughness and storage), followed, if warranted, by modified Scheffé multiple means modified t-tests ( $\alpha = 0.05$ ).

All fractured surfaces were viewed with a stereo microscope and selected fractured surfaces were further characterized with a scanning electron microscope (SEM) (Zeiss Supra 55 VP, Zeiss, Germany), operated at 10 kV, to evaluate crack propagation path and surface morphology.

### 3. Results

The SBS,  $IK_{IC}$  and  $K_{IC}$  results, along with the statistical analysis results, are summarized in Table 1; Box plots of the results are shown in Fig. 1a/b.

The analysis of the SBS results has identified a significant difference between the 60 grit preconditioned group and the other groups, both after 24 h storage in 37 °C water and after thermocycling. The analysis has also identified a statistically significant decrease in SBS in all the groups as a consequence of thermocycling.

The analysis of the  $IK_{IC}$  results has shown no significant differences due to surface preparation after 24 h storage in 37 °C. After thermocycling, there was a significant difference

between the 60 grit and the 600 grit preconditioned groups. The  $K_{IC}$  of the RCLA was significantly higher than the  $IK_{IC}$  of all groups, both after 24 h storage in 37 °C water and after thermocycling. The analysis has also identified a statistically significant decrease in  $IK_{IC}/K_{IC}$  in all the groups as a consequence of thermocycling.

For the 24 h SBS tests, evaluation of surface morphology under light microscope identified significant damage of the RCB in 17 of the 20 60 grit samples, in 8 of the 20 320 grit samples, and mainly cohesive failure in the adhesive in the 600 grit samples. For the thermocycled SBS tests, evaluation of surface morphology under light microscope identified “subsurface damage” (SSD) (i.e. visible cracking running into the bulk) of the RCB in all 60 grit samples and adhesive failure at the RCB surface for the 320 grit and 600 grit samples. These observations were confirmed during SEM characterization. Figs. 2a and b show low and high magnification images of SSD, respectively, characterized by the presence of cracks on the fractured surface of RCB, cracks that extend into the bulk as well (arrows).

For the  $IK_{IC}$  tests, evaluation of surface morphology and crack propagation path under light microscope suggested adhesive failure at the RCB surface, a suggestion confirmed during SEM characterization. As the surface roughness increased, a few of the 320 grit and 60 grit TC samples showed remnants of adhesive in the grooves, suggesting the occurrence of a cohesive failure in the adhesive along with adhesive failure at the RCB surface.

It should be noted that for SBS tests all the results ( $n = 20$ /group) were included in the calculations; for  $IK_{IC}$  tests, each load-displacement curve was carefully analyzed (slope and total displacement before fracture), each fractured surface was inspected for the presence or absence of defects at the interface, and only those results that were deemed “valid” were included in the calculations. This is further discussed in the next section.

In summary, the analysis of the results lead to the rejection of the three null hypotheses since the information provided by the two tests was not the same, surface roughness did affect

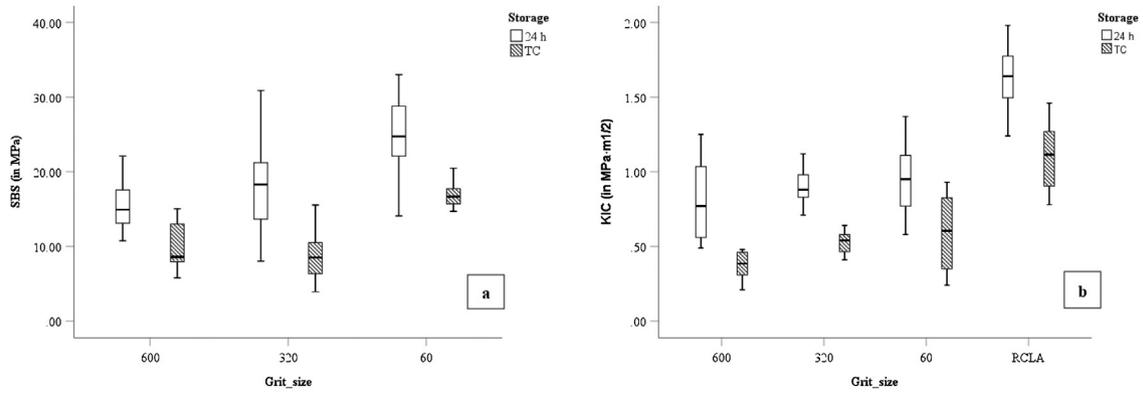


Fig. 1 – (a) Box plot of results of shear bond strength (SBS) tests; (b) Box plot of results of fracture toughness ( $K_{IC}$ ) tests.

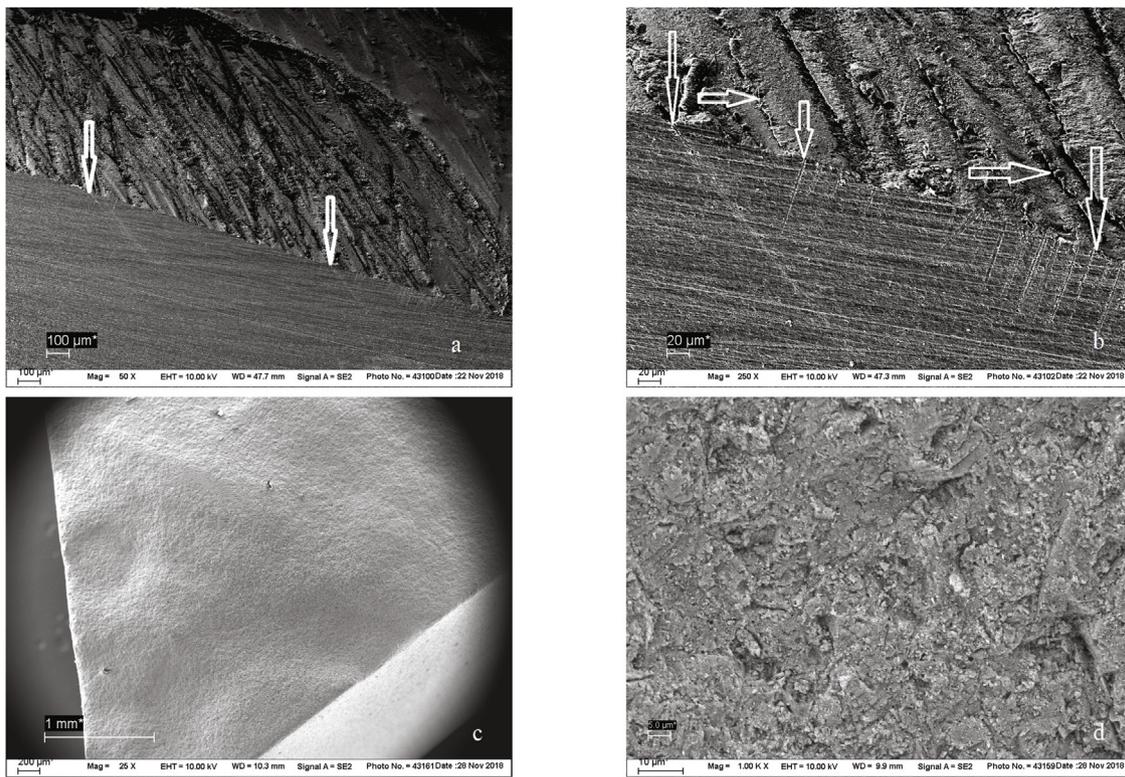


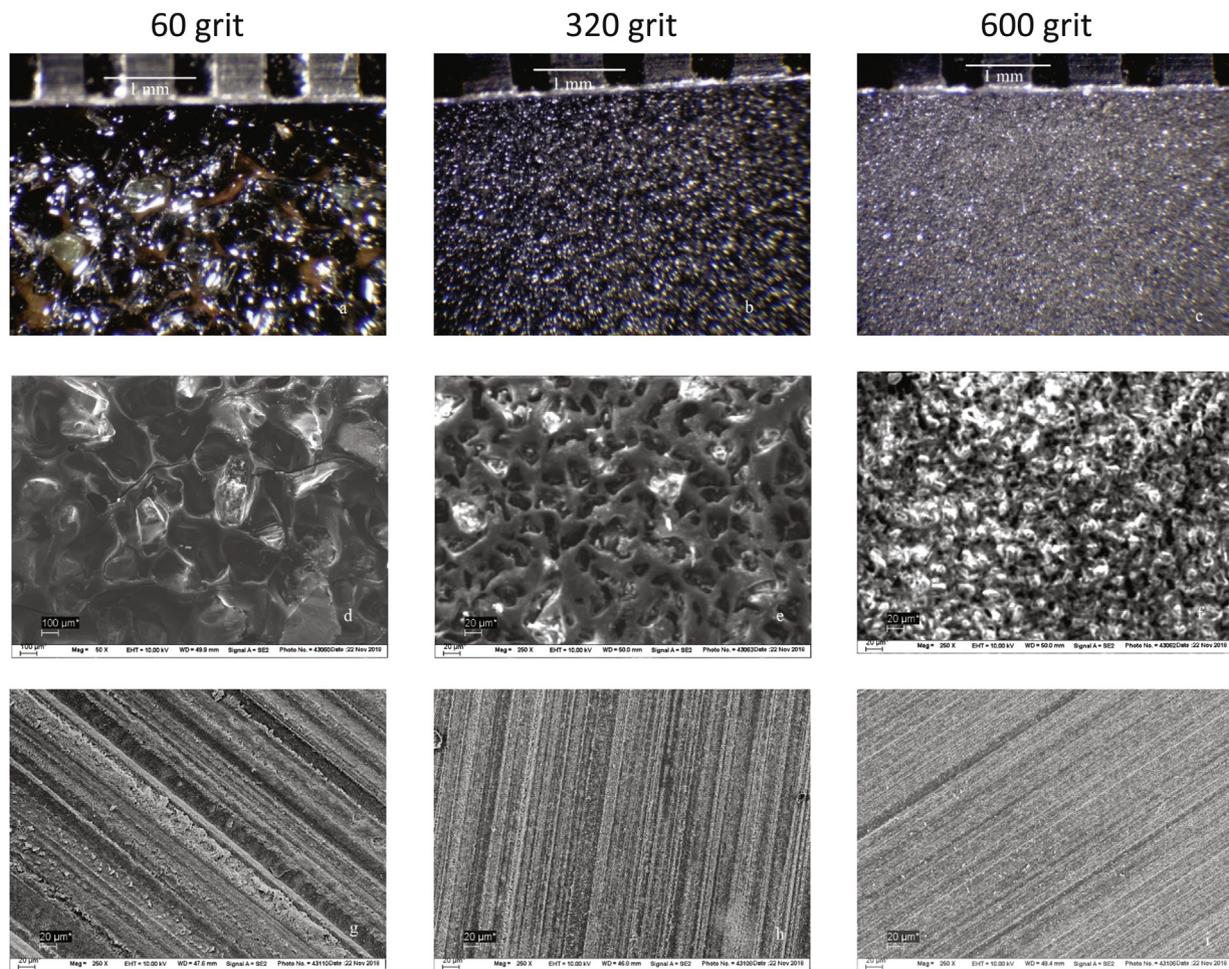
Fig. 2 – (a), (b) Cross-section through the adhesive interface of a SBS-tested 60 grit SiC thermocycled sample, showing “subsurface damage” 50 $\times$  and 250 $\times$ , respectively; arrows identify some of the surface and in-bulk cracks developed during SBS test; (c), (d) Sandblasted CAD/CAM resin composite block surface, 25 $\times$  and 1000 $\times$ , respectively.

the results obtained and TC led to a significant decrease in the determined values.

#### 4. Discussion

Characterization of adherence is conducted in order to determine not only the strength of adhesion but to also identify the weakest interface/interaction. In the present study, the adherence between a CAD/CAM RCB and a RCLA, mediated by a dental adhesive, was characterized by two methodologies, SBS and  $IK_{IC}$ . According to the thermodynamic theory of

adhesion (Dupré’s equation), the maximum work of adhesion ( $W_{a_{max}}$ ) is limited by the cohesive strength of the adhesive,  $2\gamma_L$ , where  $\gamma_L$  is the free surface energy of the adhesive [16]. In the system evaluated in this study, the cohesive strength of Adhese Universal would be the limiting factor. If the tests were to assess adherence correctly, one would expect failure to occur in one of the three valid modes of failure: (1) adhesively at one of the two interfaces involved, i.e. RCB – adhesive or RCLA – adhesive; (2) cohesively through the adhesive; or (3) in a mixed mode, when the cohesive strength of the adhesive is similar in magnitude with one or both adhesive interfaces [1]. The first aim of this study was to compare SBS and  $IK_{IC}$  test



**Fig. 3 – (a), (b), (c) – Light microscope images of sandpapers; (d), (e), (f) – SEM micrographs of sandpapers; (g), (h), (i) – SEM micrographs of resin composite block surfaces obtained with the different grit sandpapers.**

methodologies to assess their applicability to the assessment of adherence.

In the present study, with the configuration used for the implementation of the SBS test, a large number of 24 h 60 grit and 320 grit samples exhibited significant cohesive failure in the RCB (CB), while all the TC 60 grit samples showed significant SSD (Fig. 2a and b). These findings highlight the fact that stresses during SBS are not concentrated at the adhesive interface, as had been suggested and demonstrated many years ago [3,4,17]. Based on the recommendations made by Scherrer et al. [1] to exclude specimens that do not show one of the four acceptable modes of failure, the 24 h 60 grit and 320 grit results as well as the thermocycled 60 grit results presented in Table 1 should be disregarded as invalid. Based on the results obtained in this study, only surfaces prepared with 600 grit resulted in “valid” failure modes in both 24 h and TC SBS tests. This confirms the recommendation made by Mc Innes et al. [12] to use 600 grit SiC as a preferred surface roughening procedure for BS testing. It should be also mentioned that since stresses developed during SBS testing are not concentrated at the adhesive interface it is not warranted to conduct a fractographic characterization of fractured surfaces.

In the present study, with the methodology used for the implementation of  $IK_{IC}$  tests, several samples had to be excluded. In retrospect, the possible causes for rejecting samples were due either to incomplete polymerization through the 6 mm RCLA or to the effect of polymerization shrinkage of bulk (6 mm) RCLA during sample preparation, leading to weak interfacial adhesion. The authors' first attempt in preparing  $IK_{IC}$  samples involved incremental polymerization, which resulted in specimens failing at the junction between RCLA layers during  $IK_{IC}$  testing. Six groups of specimens had to be discarded and bulk polymerization was subsequently used. It should be emphasized that in incrementally bonded samples there was no failure at the block-composite interface, which led us to conclude that polymerization shrinkage was the cause of inadequate bonding when bulk polymerization was conducted. Unfortunately, the RCLA used in this study, which is to be used in a thin layer as a luting agent, may be unsuitable for incremental buildup. However, it should be noted that failure mode was “valid” in all  $IK_{IC}$  tests performed, occurring mainly at the RCB-adhesive interface, with occasional cohesive failures in the adhesive layer. This fact further supports the application of fracture mechanics methodology

in the characterization of adherence, as previously recommended by others [1,5,7,18–20].

To calculate SBS, the maximum load at fracture is divided by the macroscopic surface area of contact, which neglects the increase in surface area created by preconditioning procedures. The second aim of this study was to assess the effect of increased surface area on SBS and  $IK_{IC}$ . The average SiC particle size present on the 60 grit paper is 250  $\mu\text{m}$ , on the 320 grit is 40  $\mu\text{m}$ , and on the 600 grit is 15  $\mu\text{m}$  (LM images in Fig. 3a, b, c, respectively; SEM micrographs in Fig. 3d, e, f, respectively). The effect of these papers on the surface morphology of the RCB is presented in the SEM micrographs in Fig. 3g, h, i, respectively. A significant difference in the resulting surface roughness is observable. According to TedPella Inc. (one manufacturer of SiC paper), the surface roughness (Ra) produced by these papers on steel is 1140  $\mu\text{m}$ , 230  $\mu\text{m}$ , and 110  $\mu\text{m}$ , respectively, while according to the measurements reported by McInnes et al., Ra produced by these papers on dentin is 3.8  $\mu\text{m}$ , 0.6  $\mu\text{m}$ , and 0.1  $\mu\text{m}$ , respectively [12]. The increased surface roughness afforded by 320 grit and 60 grit resulted in catastrophic bulk failure in RCB during SBS testing. This finding adds support to the previously reached conclusion that 600 grit SiC paper should be used for SBS tests [12].

It should be highlighted that the time required for the sample preparation procedures for the two investigated test methodologies was relatively the same. However, the custom made jigs and fixtures required for sample preparation and  $IK_{IC}$  testing require a significant initial investment (>US\$5000) and should be manufactured with low tolerances.

It should also be noted that the authors are cognizant of the fact that many manufacturers and many authors [21–23] recommend sandblasting as a preconditioning procedure for CAD/CAM RCB. However, in our opinion, sandblasting leads to the formation of subsurface cracks on the intaglio aspect of crowns, which could, eventually, compromise their long term fatigue properties and lead to catastrophic failure [24]. Moreover, unintentional exposure of crown margins to sandblasting could result in clinically unacceptable marginal gaps. To substantiate our point, we sandblasted a NTP specimen with 50  $\mu\text{m}$   $\text{Al}_2\text{O}_3$  under 0.1 MPa from 5 cm for 5 s and characterized the resulting surface under SEM. The low and high magnification SEM micrographs presented in Fig. 3c and d clearly show the detrimental results of this procedure.

The second aim of this study was to assess the adherence of a RCLA to a CAD/CAM RCB, mediated by an adhesive from the same manufacturer. At 24 h, based only on the SBS tests results obtained by roughening the surface with 600 grit SiC paper (deemed valid by the discussion above) and on LM/SEM characterization of fractured surfaces, it could be concluded that SBS was relatively low ( $\bar{17}$  MPa) and that the weak link was, in the majority of cases, the cohesive strength of the adhesive. At 24 h, based on the  $IK_{IC}$  tests results, it could be concluded that there was no difference between the three SiC grit groups ( $\bar{0.9}$  MPa  $\text{m}^{1/2}$ ) and that the weak link was primarily at the RCB-adhesive interface with occasional cohesive failures in the adhesive. The 24 h  $IK_{IC}$  determined are significantly lower than the 24 h  $K_{IC}$  determined for the RCLA (1.62 MPa  $\text{m}^{1/2}$ ). These findings highlight the fact that the pur-

ported “good bonding” capabilities to CAD/CAM RCB may not actually be true. Furthermore, the findings suggest that  $IK_{IC}$  may be better than SBS at identifying the weak link in an adhesive interface.

The third aim of this study was to assess the effect of thermocycling on SBS and  $IK_{IC}$ . The results of this study showed a significant decrease in all the groups as well as in the  $K_{IC}$  of the RCLA. This finding suggests that results of 24 h tests, which represent the majority of the data reported in the literature [1], are not to be considered relevant in the prognosis of long-term performance of adhesive interfaces or resin-based materials. Similar conclusions have been reached previously and, unfortunately, the recommendation to use a minimum number of thermocycles [14] is often ignored, even by dental ISO standards.

## 5. Conclusions

The results of this study endorse the use of fracture mechanics methodology for the assessment and characterization of adherence, while identifying some difficulties in its implementation. The results also suggest that adherence to CAD/CAM RCB may be limited by the strength of the RCB-adhesive interface.

## Acknowledgment

Support from the Center for Advanced Studies (CAS) of the Ludwig-Maximilians-Universität München, Germany

## REFERENCES

- [1] Scherrer SS, Cesar PF, Swain MV. Direct comparison of the bond strength results of the different test methods: a critical literature review. *Dent Mater* 2010;26:e78–93.
- [2] Armstrong S, Geraldeli S, Maia R, Raposo LH, Soares CJ, Yamagawa J. Adhesion to tooth structure: a critical review of “micro” bond strength test methods. *Dent Mater* 2010;26:e50–62.
- [3] van Noort R, Noroozi S, Howard IC, Cardew G. A critique of bond strength measurements. *J Dent* 1989;17:61–7.
- [4] van Noort R, Cardew GE, Howard IC, Noroozi S. The effect of local interfacial geometry on the measurement of the tensile bond strength to dentin. *J Dent Res* 1991;70:889–93.
- [5] DeHoff PH, Anusavice KJ, Wang Z. Three-dimensional finite element analysis of the shear bond test. *Dent Mater* 1995;11:126–31.
- [6] Ruse ND. Fracure mechanics characterization of dental biomaterials. *Dental Biomaterials* 2008;261–93.
- [7] De Munck J, Luehrs AK, Poitevin A, Van Ende A, Van Meerbeek B. Fracture toughness versus micro-tensile bond strength testing of adhesive-dentin interfaces. *Dent Mater* 2013;29:635–44.
- [8] Ruse ND, Sadoun MJ. Resin-composite blocks for dental CAD/CAM applications. *J Dent Res* 2014;93:1232–4.
- [9] Mainjot AK, Dupont NM, Oudkerk JC, Dewael TY, Sadoun MJ. From artisanal to CAD-CAM blocks: state of the art of indirect composites. *J Dent Res* 2016;95:487–95.
- [10] Phan AC, Béhin P, Stoclet G, Ruse ND, Nguyen JF, Sadoun M. Optimum pressure for the high-pressure polymerization of urethane dimethacrylate. *Dent Mater* 2015;31:406–12.

- [11] Eldafrawy M, Ebroin MG, Gailly PA, Nguyen JF, Sadoun MJ, Mainjot AK. Bonding to CAD-CAM composites: an interfacial fracture toughness approach. *J Dent Res* 2018;97:60–7.
- [12] McInnes PM, Wendt Jr SL, Retief DH, Weinberg R. Effect of dentin surface roughness on shear bond strength. *Dent Mater* 1990;6:204–7.
- [13] Ruse ND, Troczynski T, MacEntee MI, Feduik D. Novel fracture toughness test using a notchless triangular prism (NTP) specimen. *J Biomed Mater Res* 1996;31:457–63.
- [14] Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. *J Dent* 1999;27:89–99.
- [15] van Belle G. Statistical rules of thumb. 2nd ed; 2008. p. 27–51.
- [16] Baldan A. Adhesion phenomena in bonded joints. *Int J Adh Adh* 2012;38:95–116.
- [17] Versluis A, Tantbirojn D, Douglas WH. Why do shear bond tests pull out dentin? *J Dent Res* 1997;76:1298–307.
- [18] Ferracane JL, Hilton TJ, Sakaguchi RL. Introduction to and outcomes of the conference on adhesion in dentistry. *Dent Mater* 2010;26:105–7.
- [19] Ferracane JL, Lohbauer U, Palin WM. The mechanical behavior of the material-tissue and material-material interface in dental reconstructions. *Int J Adh Adh* 2016;69:2–14.
- [20] Tantbirojn D, Cheng YS, Versluis A, Hodges JS, Douglas WH. Nominal shear or fracture mechanics in the assessment of composite-dentin adhesion? *J Dent Res* 2000;79:41–8.
- [21] Elsaka SE. Bond strength of novel CAD/CAM restorative materials to self-adhesive resin cement: the effect of surface treatments. *J Adhes Dent* 2014;16:531–40.
- [22] Peumans M, Valjakova EB, De MJ, Mishevska CB, Van MB. Bonding effectiveness of luting composites to different CAD/CAM materials. *J Adhes Dent* 2016;18:289–302.
- [23] Mine A, Kabetani T, Kawaguchi-Uemura A, Higashi M, Tajiri Y, Hagino R, et al. Effectiveness of current adhesive systems when bonding to CAD/CAM indirect resin materials: a review of 32 publications. *Jpn Dent Sci Rev* 2019;55:41–50.
- [24] Yoshihara K, Nagaoka N, Maruo Y, Nishigawa G, Irie M, Yoshida Y, et al. Sandblasting may damage the surface of composite CAD-CAM blocks. *Dent Mater* 2017;33:e124–35.