

Imagistic Evaluation of the Orthodontics Interfaces

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Abstract. In orthodontics, the scientific interest regarding adhesion is focused on optimizing adherents: metallic or aesthetic bracket base conditioning, creating aesthetic brackets with improved mechanical properties, enamel conditioning and artificial surface conditioning (aesthetic veneers and crowns). In order to investigate the interfaces between adherents there are several invasive (destructive) methods such as tensile bond strength tests, shear bond strength tests and microleakage tests.

The aim of this paper contributes to the development of the state of the art, especially by introducing new investigation techniques and thus allowing a more complex characterization in comparison to the existing ones. The innovative methods are represented by numerical simulation, optical coherence tomography (working in Time Domain Mode) and computed micro tomography (micro-CT).

Non-uniform microstructural defects that can be induced during the manufacturing process can detrimentally influence the fixation of the bracket on the tooth and its integrity.

The investigation of the interfaces was performed using a non-invasive technology - optical coherence tomography (OCT). The authors were able to characterize both the interface and fracture lines appeared at the interface using OCT.

The synchrotron radiation micro-CT technique was also employed to obtain 3D microstructural information, visualize the interfaces and observe defects, such as porosities in the adhesive layer, in a non-destructive way. Furthermore, an adhesive layer thickness analysis was performed.

Introduction

Adhesive techniques have gained many applications in dentistry, over the past couple of years. In orthodontics, adhesion is focused on optimizing adherents: metallic or aesthetic bracket base conditioning, aesthetic brackets with improved properties, enamel and artificial surface conditioning (aesthetic veneers and crowns). There are also many comparative studies emphasizing on different adhesive systems and brackets.

Modern orthodontic procedures include: fixed attachments bonded on the previously etched enamel surface, including the second molars [1]. The research proved that molar bonding was only successful in half of the cases, while cementing bands on first molars proved to have a higher rate of success. [2]. Masticatory forces in the molar region are paramount factors of success or failure in molar bonding [2]. Adolescents exercise up to up to 360 N of force in the molar region [3]. Other

factors of molar bonding are, operator accessibility, moisture control, bite depth and patient dietary co-operation [2]. Normal orthodontic forces produce stresses between 3 and 7.8 MPa. Values from 6 to 8 MPa are suggested for ex vivo bond evaluations[4].

Variables associated with shear bond strength are, the size, design and surface treatment of the adhesive contact surface [5]. Manufacture defects have been pointed out. Injection molding is based on the process of sintering metal powders. This leads to a rougher surface attachment than the machined or cast ones [6]. Roughness is highly desirable for a larger surface area base, which aids bonding. Casting and injection molding provide less fine surfaces. Roughness of the slot bottom increases friction while hindering the arch wire sliding. Kusy et al studied surface roughness of orthodontic wires [7]. Very rough surfaces cause high friction due to interlocking of peaks and valleys. The macroscopic contact area is misleading, contribution of peaks and valleys to friction are measured using atomic force microscopy (AFM) [8]. Insufficient passivation and surface defects are also variables that affect the attachments bonding.

Improving the bond strength means developing the bracket adhesive pad and reducing the base sizes [9]. The aesthetically conscious world we live in has led to the refinement of bracket base design, without sacrificing bond strength [10, 11]. Patents provide very little information regarding the dimensions of the bases [12]. Factors determining bracket base are: oral hygiene, bond strength and aesthetics [13, 14].

Seventy five percent of brackets with simple foil mesh base fail at the bracket adhesive interface [15]. Stainless steel brackets have a mesh design on the adhesive surface of the base [16]. Openings of the bracket base are determined by the wire diameter and mesh spacing. Air needs to be able to escape by means of the free volume between the mesh and the bracket base [17]. Design wise, the mesh number and the wire diameter are the most important. Retentive surface enlargement improves adhesion and increases the risk of fracture at the interface [18]. Substantiating the finding by MacColl [17] shear bond strength is independent of base size once if the bracket exceeds 7 mm². After mechanical tests, adherent surfaces undergo optical microscopy, electronic microscopy or atomic force microscopy investigations. Useful investigations may be represented by electronic microscopy, the electrochemical technique and capillary porometry (first used in industry).

Computed micro tomography (micro-CT) is a non-destructive imaging technique which uses X-rays to create high resolution (few microns) cross-sections images through a specimen which can later be reconstructed as a 3D model. Micro-CT was intensively used for bone [19, 20] and bone tissue engineering [21, 22], tooth investigations [23, 24] and other medical and technological fields [25, 28].

Micro-CT is similar to conventional computed tomography (CT) used in medical diagnosis. Micro-CT is capable of achieving a spatial resolution of up to 0.3 microns. X-rays delivered by Synchrotron Facilities offers a high photon flux, guarantees a high spatial resolution with high signal-to-noise ratio, the beam is tunable, allowing measurements at different energies and monochromatic X-ray radiation, eliminating beam hardening effects, a parallel beam and tomographic 3D reconstruction algorithms. Micro-CT 3D computed reconstruction can be sliced along any direction to gain information on the internal geometric properties and structural parameters of the sample..

Synchrotron radiation as it allows us to choose the energy of the X-ray beam. To visualize the enamel, adhesives and bracket interfaces, minimum energy is required. Visualization of the adhesive layer and its morphology is possible with a low energy level. A micro-CT experiment involving synchrotron radiation sets the X-ray beam energy to a value that allows the proper imaging of the specimens.

The pure absorption experimental set-up means the sample is extremely close to the detector, to reduce blurring. The cross section in elastic scattering of X-rays causes a phase shift of the wave, much greater than the one for absorption. Phase-contrast X-ray imaging technique was used to investigate samples in medicine, tissue engineering and regenerative medicine [29]. The phase-contrast effect underlines the edge between different materials and can be used to analyze interfaces and to better visualize the porosity inside different materials.

Materials and Methods

Forty non-carious and crack-free extracted human teeth were collected and stored in tap water at 4-6°C until processing. All teeth were professionally cleaned with pumice and rotary brushes. In order to maintain a constant quality, the brushes were changed after each tooth. Metallic (5 samples), polymeric (5 samples) and ceramic (5 samples) brackets were used for this study. After cleaning, the vestibular surfaces were etched with 38% ortho-phosphoric acid for 30" then thoroughly rinsed with water spray and carefully and completely dried with air spray. A bonding agent was subsequently applied with a brush to the etched the vestibular surfaces and to the base of each bracket, and thinned with a gentle stream of air. Self-curing composite resin was placed on the bracket base and the bracket was firmly pressed onto the conditioned enamel surface. Excess composite was removed with a probe.

The sample teeth were then probed using the Time Domain Optical Coherence Tomography System that was working at 1300 nm (Figure 1). Optical coherence tomography (OCT) is a non-invasive optical investigation technique that allows obtaining high performance resolutions and tomographic images in a transverse section of structures. Light penetrates samples in a noninvasive manner. The different degree of light refraction is used in order to generate a signal corresponding to the composition of the studied structures. The major advantage of this technique resides in its higher resolution (1-10 microns) compared to the radiographic technique (50 microns) or ultrasound (110 microns). In dentistry OCT has proved to be useful in obtaining high fidelity images of dental restorations [30]. Using a suitable light source (in terms of wave length) one can achieve a higher penetration depth. In case of using a 1300 nm wavelength, light can penetrate the tooth on about 2-3mm. The calibration and measurements on the OCT slices were performed with the 1951 USAF test pattern (Edmund Optics) in chrome pattern on clear background.



Figure 1. The aspects from the Time Domain OCT investigations.

A synchrotron radiation X-Ray micro-CT experiment was performed at the SYRMEP Beamline of the ELETTRA Synchrotron Radiation Facility (Trieste, Italy). The 1200 radiographic projections were acquired with a beam energy of 29 keV over 180° with a pixel size of 9 μm . A sample – detector distance of 16 cm was considered in order to have both absorption and phase-contrast signal, for a better viewing of the interfaces (Figure 2).

The tomographic reconstruction was performed by means of the common filtered back-projection method [31].

For 3D visualization, data volumes were rendered directly without decomposing them into geometric primitives. A Quad-Core Processor 2.01 GHz PC with 8 Gb RAM and a commercial software VGStudio MAX 1.2 were used to generate 3D images and to visualize distribution in 3D of different constituents, namely dentine, enamel, adhesive and bracket. In order to achieve optimal settings for the image quality, a Scatter HQ algorithm was employed with an oversampling factor of 4.0 and activated colour rendering.



Figure 2. *Micro-CT investigations using the Synchrotron Radiation at the SYRMEP Beamline of the ELETTRA Synchrotron Radiation Facility (Trieste, Italy).*

Results

The imagistic results pointed out the quality of the bracket/adhesive/enamel interfaces. The adhesive layer presented three parts: an external part of the adhesive layer that is bonded on the enamel and on the lateral part of the bracket; an adhesive layer between the dental enamel and bracket at the first part of the bracket's base, where the layer is thinner (till 0.5 mm from the edge of the bracket base); and the internal part of the adhesive layer, bonded to the enamel and bracket base, wider than the second zone.

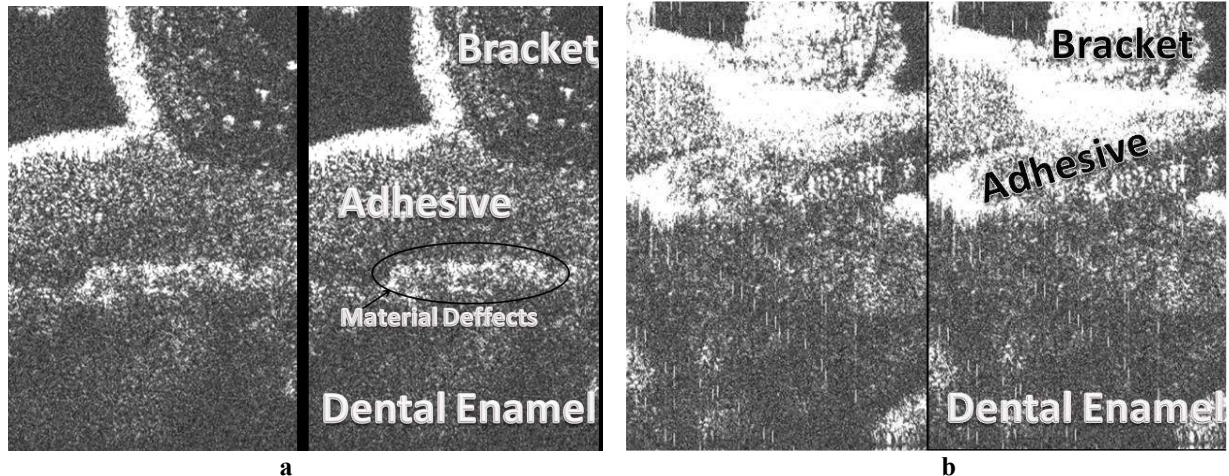


Figure 3. *The aspects of the 2D OCT Time Domain investigations of the polymeric bracket interface (a); 2D OCT Time Domain investigation of the metallic bracket interface (b).*

Material defects were found in 13 samples (32 %). These material defects were observed inside the matrix resin, between the bracket and enamel, represented by chains of small gaps (Figure 3. a, and 4. a). In 3 samples the defects were found in the external part of the adhesive layer with implications in a possible debonding of this part from the enamel and leading to future cavities near the brackets (considering that the prevention procedures are difficult in these areas). The defects were located in the second part of the adhesive layer in 2 layers, while 5 samples were discovered with defects in the central part of the layer (the most common area for defects). The rest of the three samples presented a chain like defects with different volumes, both in second and third part of the adhesive layer. These defects could lead to the possible debonding of the entire orthodontic attachments, if they will be linked under the orthodontic forces. In the metallic brackets interfaces

the OCT investigations were affected by the reflection of metallic brackets (Figure 3. b and 4. b). For these interfaces the angle of the beam should not interfere directly with the metallic parts in order to diminish the noise from the slices. The metal and ceramic bracket interfaces had together only 5 samples with defects (2 ceramic and 3 metallic) in compare with the polymeric interfaces, where the rest of the 8 defects were found.

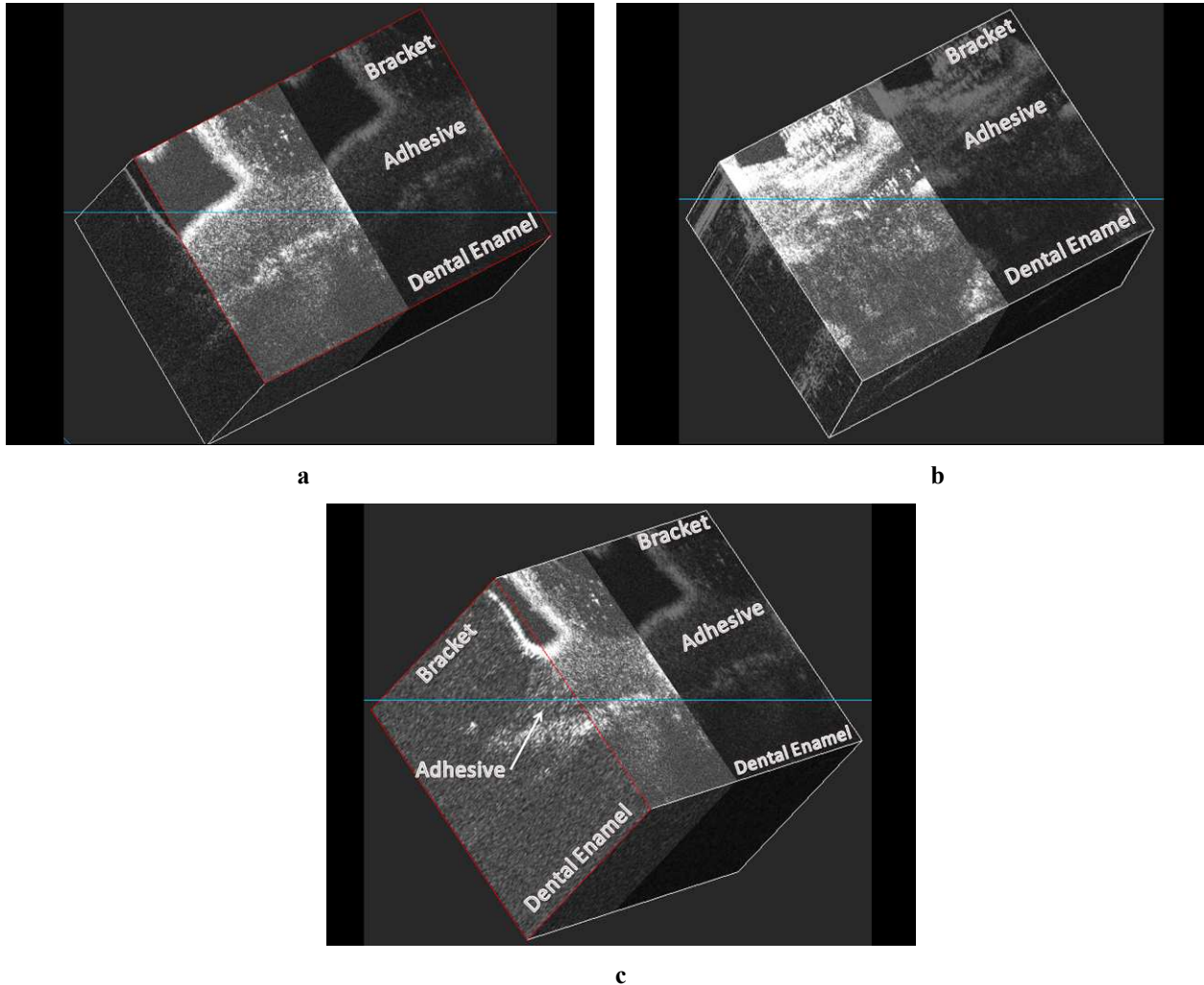


Figure 4. 3D aspect of the OCT Time Domain investigations of the polymeric bracket interface (a) and of the metallic bracket interface (b); 3D navigation inside the targeted interface (c).

The micro-CT analyses was used to non-destructively image and characterize the 3D distribution of the different components, namely the enamel, the dentine, the adhesive and the ceramic bracket. Specimens were scanned and projections were obtained by the data processing system and reconstructed into 2D images. The basic physical parameter, quantified in each pixel of an absorption micro-CT image and exploited to obtain the contrast, is the linear X-ray attenuation coefficient μ . The differences in the X-ray absorption rate within the samples translate into different peaks in the grey level scale, corresponding to the different phases. The region of interest was selected and thresholded to eliminate background noise. The thresholded 3D volumes were converted into coloured images using the VG Studio Max software. In Figure 5, the full 3D reconstruction of the tooth – bracket system is presented, all the components are visualized. For a better viewing of the enamel – adhesive – bracket interface, a section of this 3D reconstruction is showed in Figure 6 – porosity inside the adhesive can be observed.

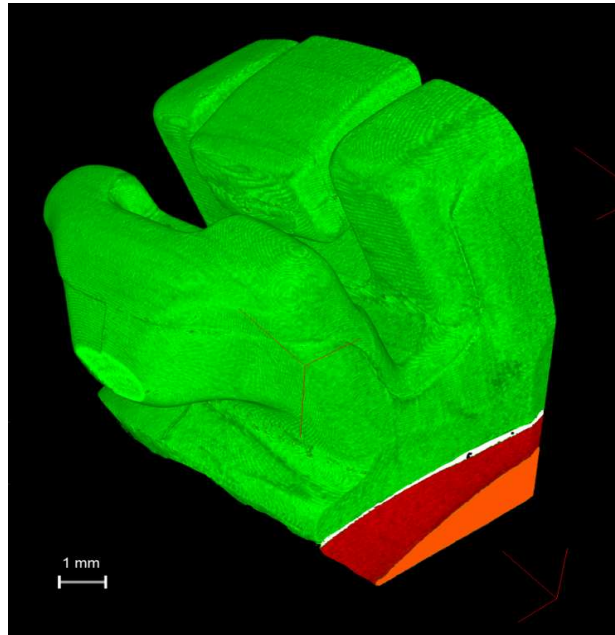


Figure 5. 3D micro-CT reconstruction of the specimen: dentine (orange), enamel (red), adhesive layer (white) and ceramic bracket (green).

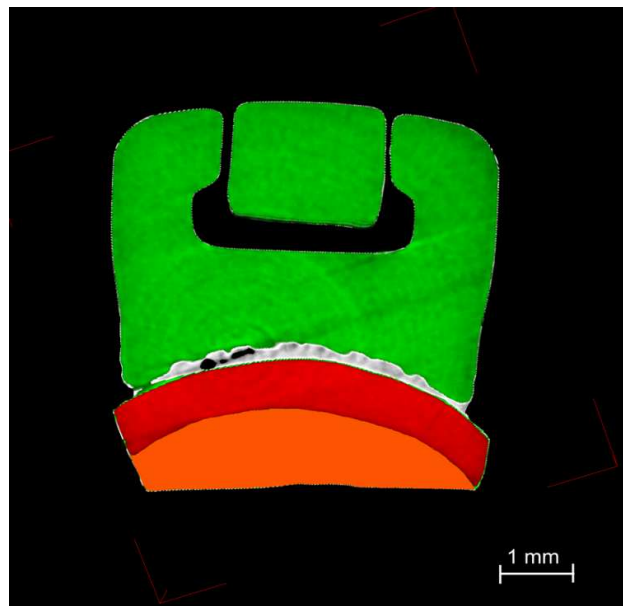


Figure 6. Cross section of the 3D micro-CT reconstruction of the specimen: dentine (orange), enamel (red), adhesive layer (white) and ceramic bracket (green).

It is also possible to use 3D image processing to make one or more phases translucent or even to ‘cancel’ a phase in order to allow a more accurate observation of the spatial distribution of each phase. In Figure 7, only the adhesive phase was left and areas with no adhesive between the enamel and the bracket were found. It was calculated that the adhesive layer had a thickness in a range from 10 to 210 microns and an average porosity of about 2.5 vol. %.

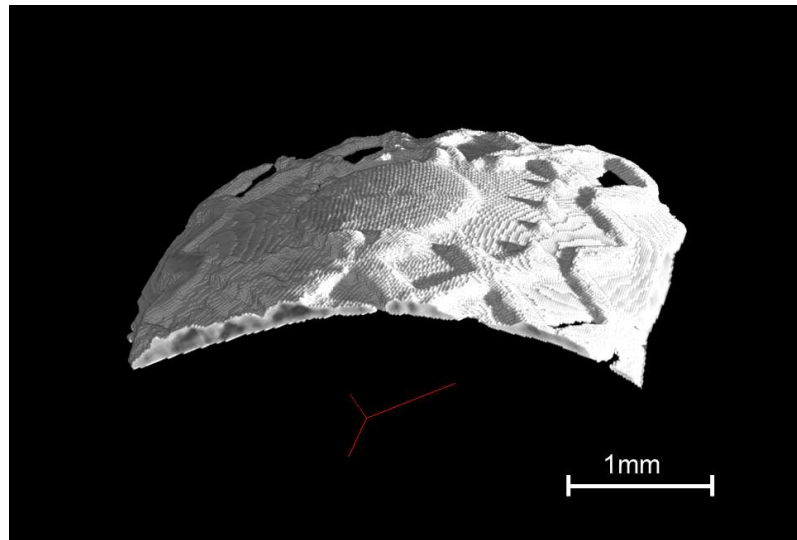


Figure 7. 3D micro-CT reconstruction of the adhesive layer

The thickness distribution of the adhesive was analyzed using a module of VG Studio MAX 1.2, namely the “Wall thickness analysis” module. Results are presented in Figure 8 and Figure 9. Different slices with no porosity are visualized in Figure 8, while from Figure 9 it can be observed that the distribution of the adhesive layer thickness is not uniform, a greater part of the adhesive layer has a lower thickness. The average width of the adhesive layer between the dental enamel and bracket at the first part of the bracket’s base, where the layer is thinner, was determined to be 65.7 microns, while in the internal part of the adhesive layer the average width was 157.8 microns. The average value of the thickness of the whole adhesive layer was 98.3 microns.

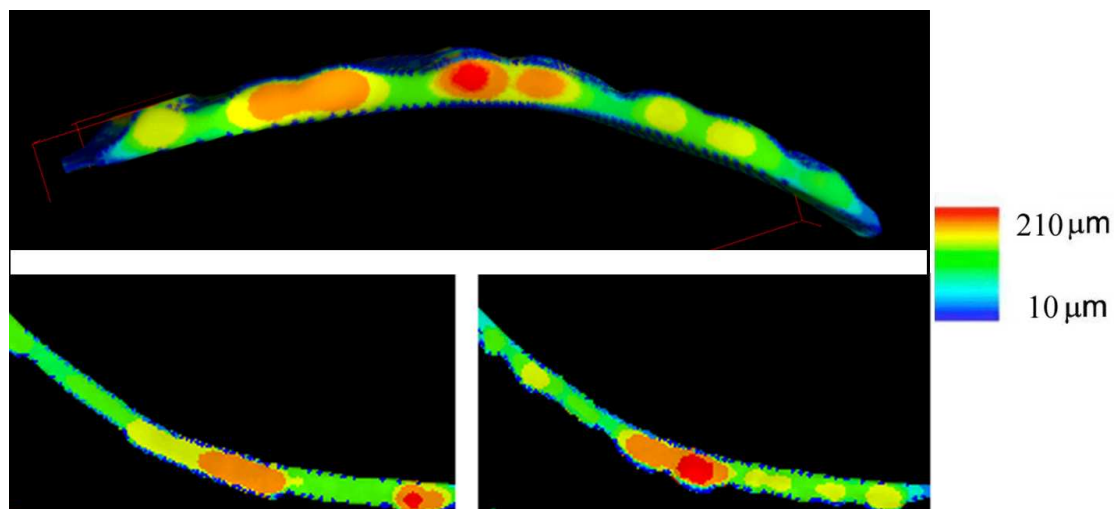


Figure 8. Color map of the adhesive layer thickness distribution.

The adhesive layers were measured both in the OCT and micro-CT technologies with the same results. Only in two probes the adhesive widths were higher with approximately 35 % than the presented values above. A debonding is possible for these samples because of the orthodontic tensions that will affect and will probably initiate a fracture in the adhesive layer.

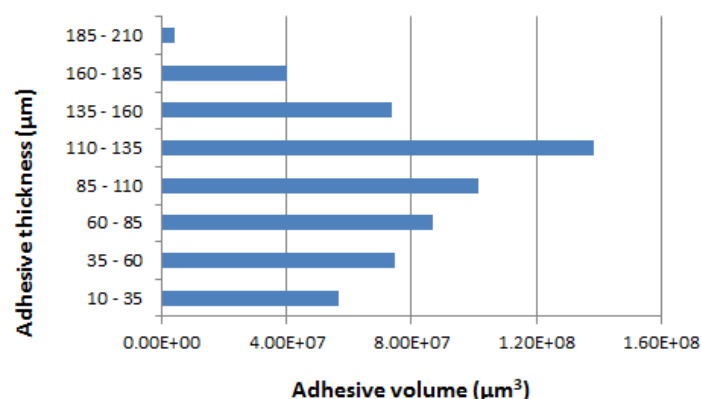


Figure 9. Adhesive layer thickness distribution.

Conclusions

The imagistic evaluation of the orthodontic interfaces is very important in the evaluation and the prognostic of the brackets bonding. Optical coherence tomography clearly proves its utility in investigating orthodontic bonding. With this non-invasive method, the material defects trapped inside the matrix resin can be localized and 3D reconstructed. For this reason, this method has a great potential for clinical use.

Synchrotron radiation micro-CT was successfully exploited for the visualization of the tooth – adhesive – bracket interfaces and for the morphologic and morphometric investigation of the adhesive layer. The micro-CT experiment confirmed the presence of porosity and interconnected porosity in the adhesive layer, as seen in the OCT analysis. Moreover, it allowed a quantification of the porosity of the adhesive layer and also the analysis of the adhesive layer thickness distribution. Further studies are necessary in order to establish a correlation between clinical acceptability of the bracket-tooth interface and gap size. An association between OCT and micro-CT investigations and subsequent mechanical testing would probably be a suitable choice in order to determine the minimum gap acceptable in clinical applications.

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