Orthodontic bracket bonding from a different angle - an optical coherence tomography investigation

Roxana Romînu, Cosmin Sinescu, Meda Negruțiu, Emanuela Petrescu, Daniela Pop, Mihai Romînu, Adrian Gheorghe Podoleanu

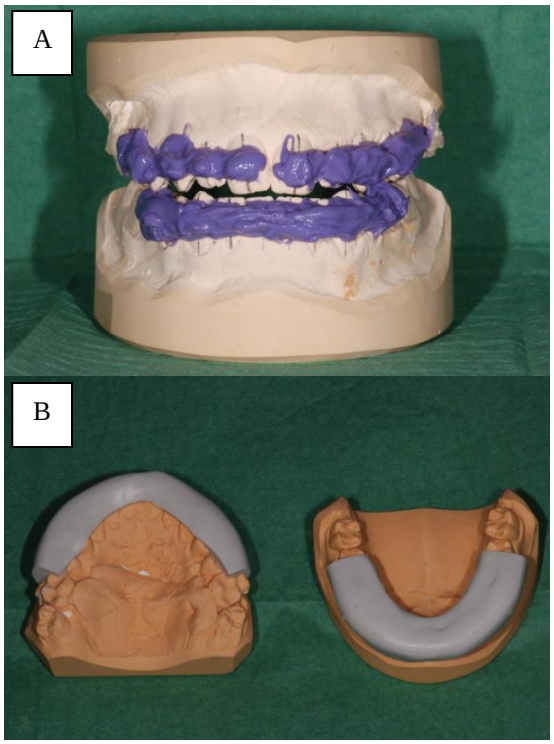
Abstract— Bracket bonding has become routine procedure in fixed orthodontics over the past couple of decades. The choice whether to receive ceramic or polycarbonate brackets is mainly the patient's but the issues related to bonding them are part of the practitioner's responsibility. Recurrent bracket debonding can unduly prolong treatment or even lead to compromised results. Therefore, we collected human extracted premolars and bonded them with aesthetic brackets and investigated them by a new, non-invasive method – optical coherence tomography (OCT) in order to assess the quality of the bracket-tooth interface. The OCT investigation revealed a series of gaps within the adhesive at the bracket-tooth interface. The importance of our research resides in the fact that this type of investigates opens a totally new perspective in dentistry due to the fact that samples are left intact and ready for further testing unlike of the majority of investigation methods available nowadays.

Keywords **—** optical coherence tomography, orthodontic bonding, orthodontic brackets, non-invasive investigations. adhesive dentistry

I. Introduction

Bracket bonding has become routine procedure in fixed orthodontics over the past couple of decades. In spite that in this field the requirements are not as high as in other branches of adhesive dentistry, since the life span of a fixed appliance is about 24 months, so shorter than that of a prostheses, we still encounter problems, especially when using tooth colored brackets. The choice whether to receive ceramic or polycarbonate brackets is mainly the patient's but the issues related to bonding them are part of the practitioner's responsibility. Recurrent bracket debonding can unduly prolong treatment or even lead to compromised results.

As far as the technical aspects of bonding are concerned, in vivo, there are two ways brackets are usually bonded: indirectly, by bonding the brackets on the study cast and trasferring them by means of a silicone/plastic tray (figures 1 and 2) or directly, by bonding them one by one. In both cases, the enamel has to be cleaned and conditioned and proper isolation from saliva is crucial.



Manuscript received October 9, 2007: Revised version received August 7, 2011. This work was supported in part by the CNCSIS Grant TE 101/2010
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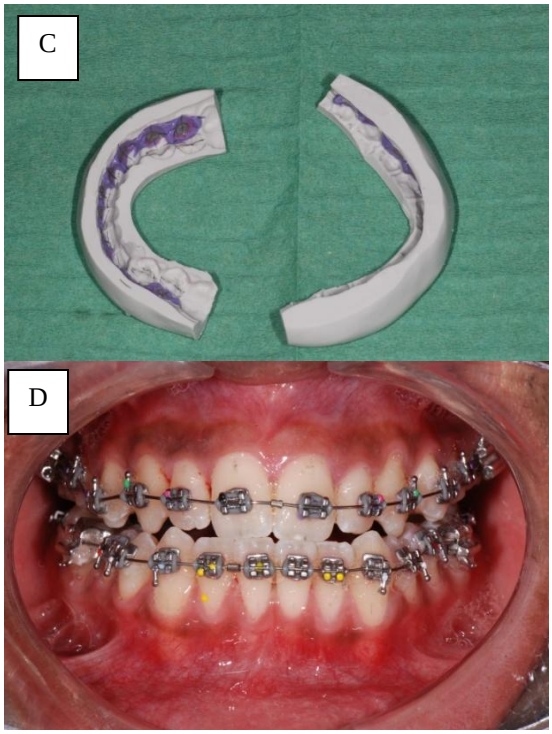

Figure 1 – A – orthodontic brackets bonded on the study cast; B – the silicone transfer tray on the study model; C – the transfer trays once ready to be inserted into the oral cavity; D – brackets bonded in place.

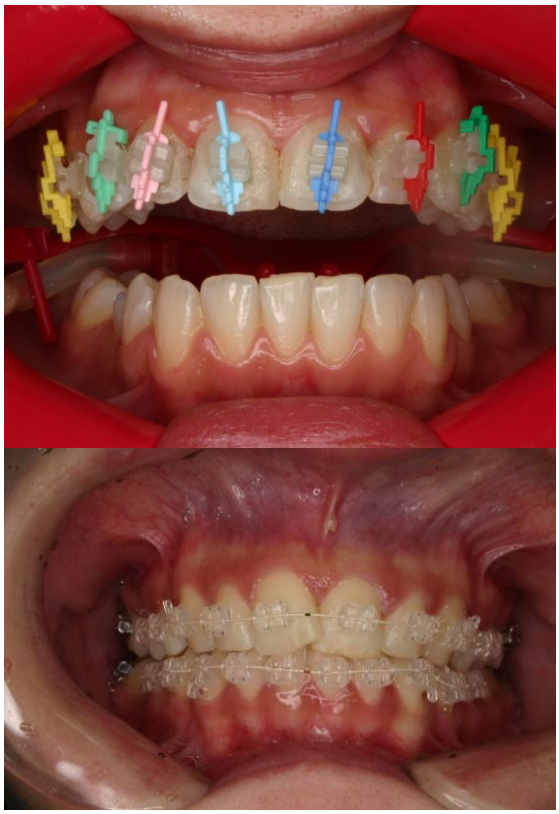

Figure 2 – Esthetic braces bonded directly onto the teeth

Polycarbonate and ceramic brackets are both aesthetic but aside from that, they don't bear any resemblance from a chemical point of view and as far as bond strength to human enamel is concerned they are exact opposites. Therefore, it seemed interesting to us to assess the tooth-bracket interface and to see whether we find any significant differences. In order to do this we used a non invasive method – optical coherence tomography, which has the great advantage that it leaves the samples intact, allowing for further testing.

Optical coherence tomography has been successfully used in ophthalmology. It is the aim of our research to explore all possibilities of this versatile investigation tool.

II. Materials and Method

During the last 20 years, optical coherence tomography (OCT) has developed into a powerful technique for imaging of transparent and translucent structures. OCT is a very attractive imaging technique for obtaining noninvasive high-resolution images and uses a low-coherence interferometer in order to acquire a micron-scale cross-sectional image.

Low coherence interferometry (LCI) has evolved as an absolute measurement technique which allows high resolution ranging) and characterization of optoelectronic components. The first application in the biomedical optics field was for the measurement of the eye length. A reflectivity profile in depth is obtained, called A-scan. A low coherence interferometry system is generally based on a two-beam interferometer. A-scan technique was facilitated by a technical advantage: when moving the mirror in the reference path of the interferometer, not only is the depth scanned, but a carrier is also generated. The carrier frequency shift frequency is the Doppler shift produced by the longitudinal scanner itself (moving along the axis of the system, Z, to explore the tissue in depth). Due to the high potential of the technique for high resolution imaging of the tissue, it is often referred to as optical coherence tomography (OCT).

To obtain 3D information about the object, any imaging system is equipped with three scanning means, one to scan the object in depth and two others to scan the object transversally. Depending on the order these scanners are operated and on the scanning direction associated with the line displayed in the raster of the final image delivered, different possibilities exist. An *en-face* OCT system operating as 1300nm and as described in previous reports [1,2] was employed. The directions in which an object can be scanned using OCT are presented in figure 3.

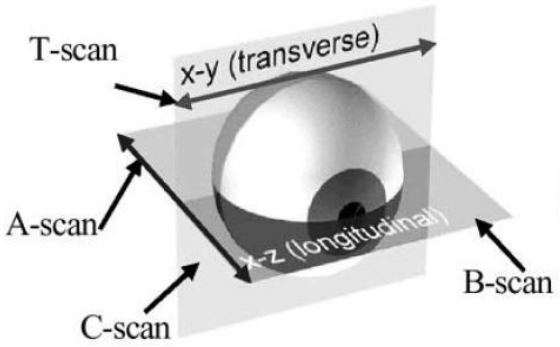

Figure 3 - Scanning directions of the OCT system

Longitudinal OCT (A-scan based B-scan)

B-scan images, analogous to ultrasound B-scan are generated by collecting many reflectivity profiles in depth (A-scans) for different and adjacent transverse positions. The transverse scanner (operating along X or Y) advances at a slower pace to build a B-scan image. The majority of reports in literature refer to this way of operation. In longitudinal OCT, the axial scanner is the fastest and its movement is synchronous with displaying the pixels along the line in the raster, while the lateral scanning determines the frame rate.

En-face OCT (T-scan based B-scan)

In this case, the transverse scanner determines the fast lines in the image. We call each such image line a T-scan. This can be produced by controlling either the transverse scanner along the X-coordinate, or along the Y-coordinate with the other two scanners fixed. This procedure has a net advantage in comparison with the A-scan based B-scan procedure as it allows production of OCT transverse (or 2D *en-face*) images for a fixed reference path, images called C-scans. In this way, the system can be easily switched from B to C-scan, procedure incompatible with A-scan based OCT imaging.

C-scan

C-scans are made from many T-scans along either of X, Y, repeated for different values of the other transverse coordinate, Y, X respectively in the transverse plane. The repetition of T-scans along the other transverse coordinate is performed at a slower rate than that of the T-scans, which determines the frame rate. In this way, a complete raster is generated. Different transversal slices are collected for different depths Z, either by advancing the optical path difference in the OCT in steps after each complete transverse (XY) scan, or continuously at a much slower speed than the frame rate. The depth scanning is the slowest in this case.
It is more difficult to generate *en-face* OCT images than longitudinal OCT images as the reference mirror is fixed and no carrier is produced. Therefore, in order to generate T-scans and T-scan based OCT images, a phase modulator is needed in order to create a carrier for the image bandwidth. This complicates the design and introduces dispersion. Research has shown that the X or Y-scanning device itself introduces a path modulation which plays a similar role to the path modulation created by the longitudinal scanner employed to produce A-scans or A-scan based B-scans (Figure 4).

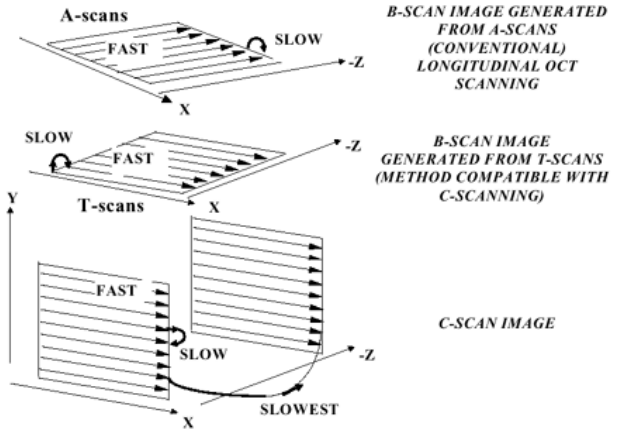

Figure 4 – Different operation modes in a typical OCT system

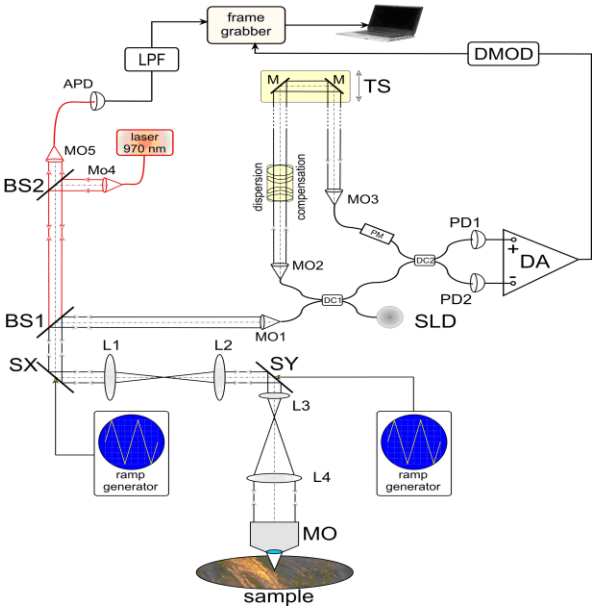

Figure 5 – Optical configuration of the system

The experimental configuration

The optical configuration [4] uses two single mode directional couplers with a superluminiscent diode as the source. The scanning procedure is similar to that used in any confocal microscope, where the fast scanning is *en-fac*e (line rate) and the depth scanning is much slower (at the frame rate) [5]. The *en-face* scans provide an instant comparison to the familiar sight provided by direct view or via a conventional

microscope [6]. Features seen with the naked eye could easily be compared with features hidden in depth. Sequential and rapid switching between the *en-face* regime and the cross-section regime, specific for the *en-face* OCT systems developed by us, represents a significant advantage in the non-invasive imaging. Images with different orientations can be obtained using the same system. As shown in figure 4, in the *en-face* regime, the frame grabber is controlled by signals from the generators driving the X-scanner and the Y-scanner. One galvo-scanner is driven with a ramp at 500 Hz and the other galvo-scanner with a ramp at 2 Hz. In this way, an *en-face* image, in the plane (x, y) is generated at constant depth. The next *en-face* image at a new depth is then generated by moving the translation stage in the reference arm of the interferometer and repeating the (x, y) scan. Ideally, the depth interval between successive frames should be much smaller than the system resolution in depth and the depth change applied only after the entire *en-face* image has been collected. However, in practice, to speed up the acquisition, the translation stage was moved continuously. Alternatively, a scanning delay line could be used, which can achieve faster depth scanning rates [7]. In the images presented below, no other phase modulation was employed apart from that introduced by the X-galvanometer scanner [8]. In Podoleanu et al [9], we demonstrated the role played by the image size in balancing the effects of an external phase modulator and of the modulation produced by the transversal scanner. If the image is sufficient large, then the distortions introduced by not using a phase modulator are insignificant.

In the cross-section regime, the frame grabber is controlled by signals from the generator driving the X-scanner (or the Y-scanner) with a ramp at 500 Hz and the translation stage moving over the depth range required in 0.5 s. In this case, an OCT cross-section image is produced either in the plane (x, z) or (y, z).

In the images presented below, no other phase modulation was employed apart from that introduced by the X galvanometer scanner, determining the line in the raster. We demonstrated in a previous study the role played by the image size in balancing the effects of an external phase modulator and of the modulation produced by the transversal scanner. If the image is sufficient large, then the distortions introduced by not using a phase modulator are insignificant.

The system operates together with a confocal microscope at a wavelength of 970 nm. This allows for the easy identification of the area of interest which can then be scanned using the OCT. Confocal microscopy can detect superficial defects itself, whereas the OCT is required to identify the deeper material defects (Figure 5). The confocal channel operates at a different wavelength than that of the OCT, to allow the utilization of a high gain silicon avalanche photodiode, APD. Light from a superluminescent diode at 970 nm is collimated by a microscope objective MO4 and reflected by a splitter BS2 (20% reflection) towards BS1. Light at 970 nm is transmitted via BS1 and BS2 towards the APD. The photo-detected signal is amplified and low pass filtered in LPF.

Sample processing and evaluation

We collected 40 crack-free, non carious extracted human first premolars and third molars. All teeth were stored in tap water at 4 ºC until they were used. In order to create the samples the teeth were professionally cleaned with pumice and rotary brushes by a single operator. In order to eliminate possible flaws the rotary brush was changed for a new one after every fifth tooth. After cleaning the teeth were thoroughly rinsed and dried and divided into two groups of 20 teeth each and subsequently bonded with ceramic (group 1) and polycarbonate brackets using a no-mix self-curing orthodontic adhesive (Figure 6) (Ortho-Loc, DentsplyGAC) following the protocol stated below:

- 30’ acid etching of the buccal surface with 37.5% orthophosphoric acid
- rinsing and drying
- applying the primer and thinning with a gentle stream of air
- applying the composite resin on the bracket based followed by pressing the base against the buccal surface
- removal of any excess adhesive with a probe

Figure 6 – The orthodontic adhesive (OrthoLoc, Dentsply GAC) used in the study

After bonding we assessed the samples using OCT [10, 11, 12, 13] in the time domain mode (Figure 7), which allowed us to detect all defects within the adhesive at the enamel-bracket base interface.

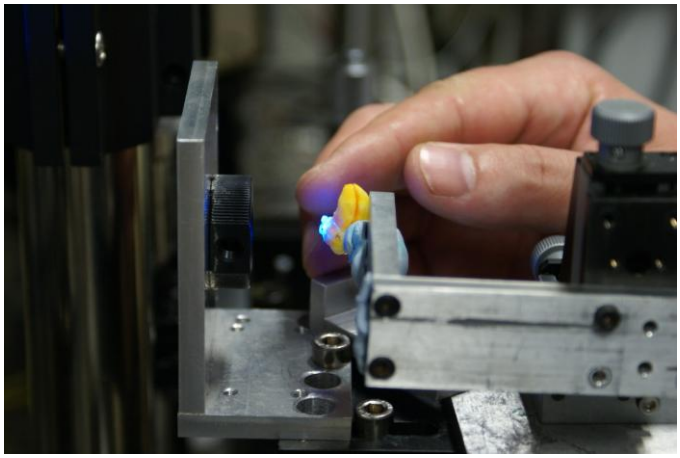

Figure 7 – Sample mounted ready to be investigated by OCT

III. Results and Discussion

Only 5 % of the overall sample number showed no detectable defects (Figure 8). Both samples from group 1 (ceramic brackets) and samples from group 2 (polycarbonate brackets) showed defects within the adhesive layer (Figure 9). The majority of the defects were aeric inclusions within the adhesive layer. A couple of samples (2 in group 1 - 10% and 3 in group 2 – 15%) showed large defects that communicated with the exterior with some lack of adhesive at the bracket base. Alltogether we found a slightly larger incidence of defects in group 2 compared to group 1.

In vivo it is impossible to detect bonding defects of this type because of the difficulty to gain access and good visibility to the surfaces of interest and of course because of the small size a scanning device had to have were it to be used in the oral cavity where space is limited.

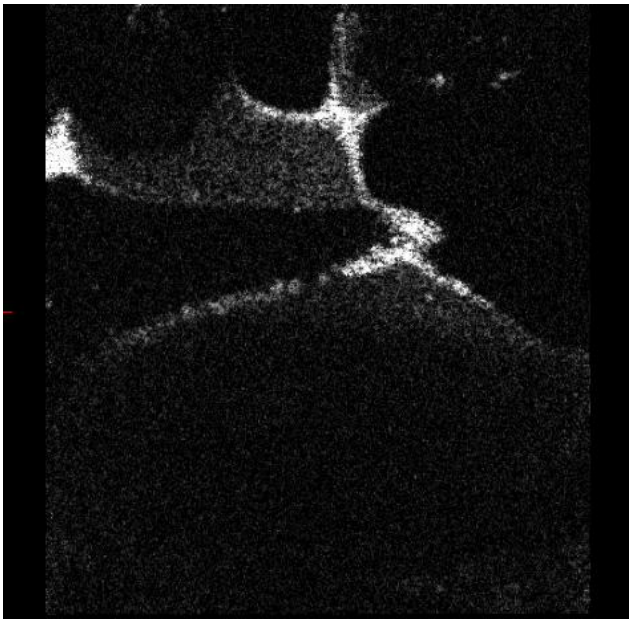

Figure 8. A sample without defects at the bracket-tooth interface. A scan at a wavelength of 1300 nm, frame 8 of 61, zoom (8 degree)

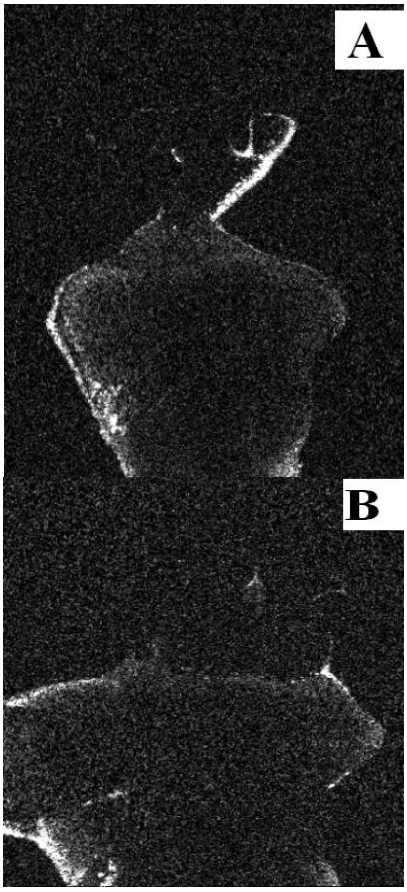

Figure 9. Material defects within the adhesive layer. A. sample from group 1, wavelength of 1300 nm, frame 10 of 61, normal scan; B. Sample from group 2, wavelength of 1300 nm, frame 19 of 61, normal scan(18 degree)

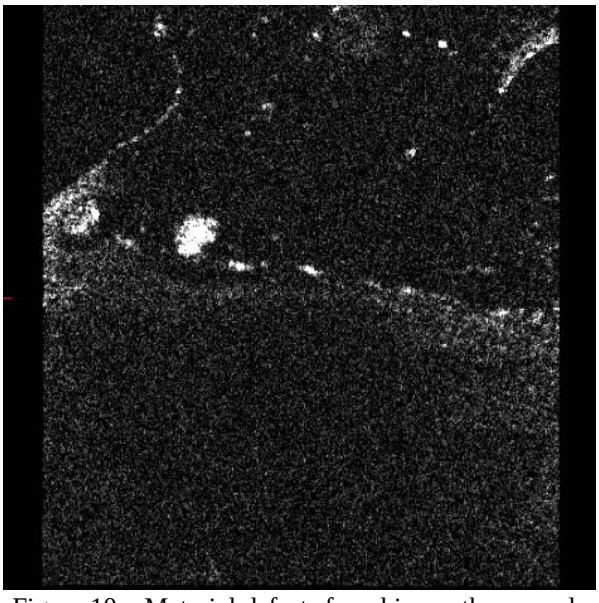

Figure 10 – Material defects found in another sample

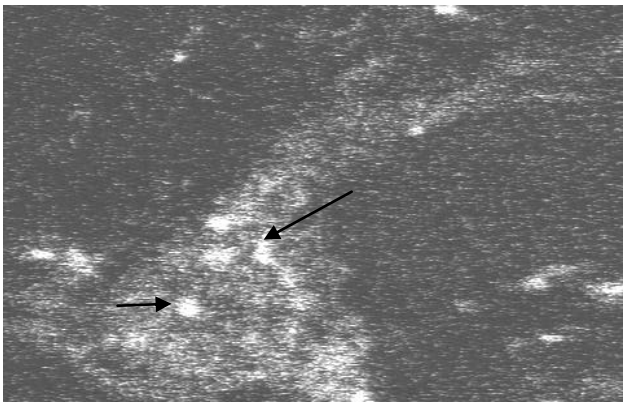

Figure 11 - Defects found within the adhesive in Sample 24

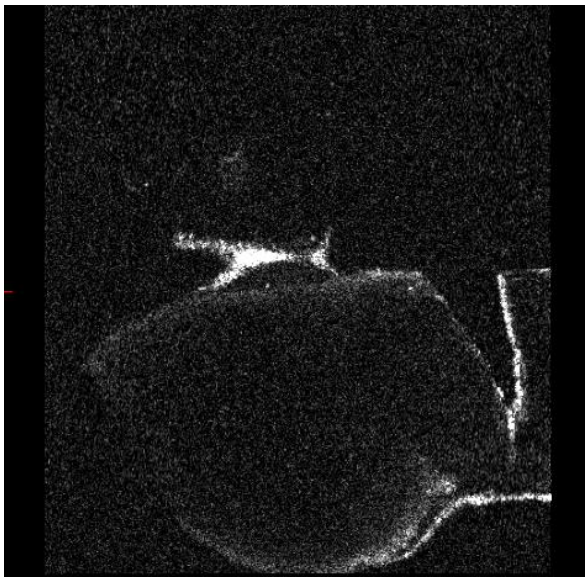

Figure 12 – Sample with mariginal bonding defect

In adhesive dentistry interfaces are being investigated *in vitro* exlusively by invasive methods. These methods include microscopic evaluations (optical microscopy, SEM, atomic force microscopy) (Figure 13), mechanical tests (where adhesive interfaces are tested for their shear bond strength and tensile bond strength by means of standardized testing devices) (Figures 14, 15).

An alternative technique is laser micro spectral analysis. First introduced in 1962 as a method of investigating the surfaces of metals, the technique has found new applications in more recent times, where it is often known as spectroscopy by laser induced plasma. A key feature of this technology is that it needs only a small quantity of the material, around 0.1g. The laser micro spectral analysis device consists of an infrared pulsed laser, usually with ruby or neodymium doped glass as the active medium. By allowing for an assessment of chemical composition of the interface area, laser micro spectral analysis can be used to establish the presence of micro leakage in the ceramic bracket enamel interfaces. It is possible to make either a semiquantitative or a quantitative analysis. However, as it requires puncturing of the sample, it is clearly an invasive procedure.

A further method for interface investigation employs Secondary Ion Mass Spectrometry (SIMS) and Sputtered Neutral Mass Spectrometry (SNMS) to obtain information on minor and major element composition. Both SIMS and SNMS methods use a focused, mono-energetic, chemically pure ion beam of typically 1-10 keV to sputter erode the surface under analysis. A small fraction of the sputtered material becomes ionized due to the sputtering process itself and, in SIMS, it is these ions that provide the high-sensitivity information for which the technique is known. Being a mass spectrometry technique, it can detect all elements and isotopes and, in favorable conditions, the detection limit can be in the low ppb region. As SIMS simultaneously sputters, erodes and detects the ion signal, it is an ideal technique to rapidly produce depth profiles of species of interest.

All these methods are destructive as samples are either sectioned or torn apart, so they can not be further investigated/used.

Not only it was possible by our method to find superficial defects [14,15], but what is really relevant to our research is the fact that we could also detect material defects within the mass of orthodontic adhesive which couldn't have been detected by visual examination. The defects can be reconstructed three-dimensionally by specialized software and measurements can be performed, which is subject to further studies.

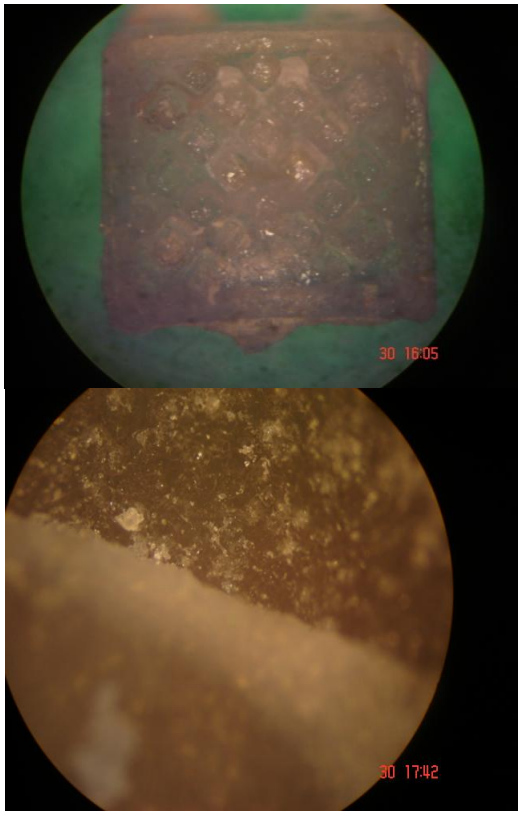

Figure 13 – Debonded esthetic brackets studied by optical microscopy

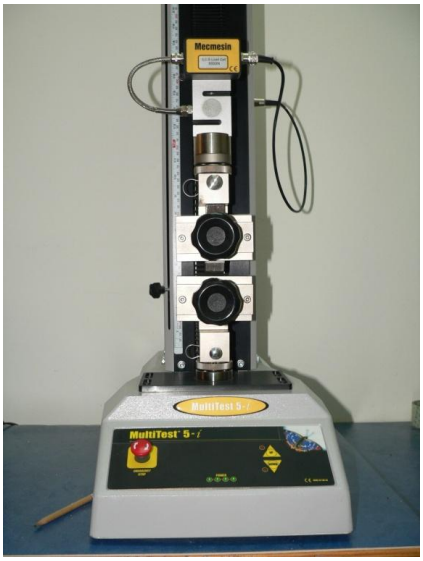

Figure 14 – Universal testing device (Multitest 5-I, Mecmesin Ltd, UK)

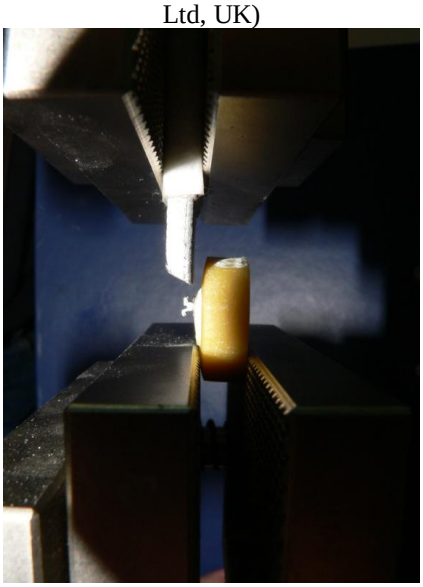

Figure 15 – A sample mounted for shear bond strength testing

IV. Conclusions

1. OCT has proved to be a very useful tool in the qualitative assessment of orthodontic bonding by being of the very few non-invasive testing methods, leaving the samples intact and ready for further testing.
2. By associating OCT with further testing methods as mechanical testing we could possibly establish a new threshold of clinical acceptability in orthodontic bonding.
3. Optical coherence tomography could potentially come to play a crucial role in checking the bonding accuracy in areas with low direct visibility and difficult access.

Acknowledgment

We hereby express our acknowledgment for the support of CNCS research project TE 101/2010.

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