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The Effect of Surface Treatments on Shear Bond Strength between Orthodontic Metal Bracket and Porcelain Face

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Abstract: **Objectives:** To report on the different approaches taken to improve the bonding of orthodontic brackets to porcelain surfaces and review the literature and test the available alternatives of hydrofluoric acid use. **Materials and Methods:** The search engine PubMed, Scopus, Google Scholar and Science Direct were used for this study to obtain relevant information. The sample comprises 18 Porcelain fused to metal crowns, etchant acids like Hydrofluoric Acid 9.6%; Orthophosphoric Acid 37%; Maleic Acid 10, 20, 30%. Acrylic tooth holder, high-speed hand piece, round bur, bonding agent, composite, brackets, bracket holder, light cure, and Universal Testing Machine were all used to conduct the study at Ajman University Prosthodontic Laboratory. **Results:** The highest shear bond strength value was observed for sandblasting without any acid etching. Maleic Acid 30% were found to have the highest shear strength amongst all other acids after 1-minute etching, while Maleic Acid 20% showed the highest value after etching for 2-minutes. Orthophosphoric Acid 37% showed the highest shear strength compared to the other acids after 3-minutes etching. **Conclusions:** Two essential factors to be considered when bonding in orthodontics is the concentration of acid being used and the amount of time subjected to the surface. Sandblasting alone without using any acid etching has the highest value, and it hails to be one of the most effective ways of increasing bond strength. Furthermore, compared with all the acids we have used, Maleic acid of 30% has shown the highest shear strength after 1-minute of etching.

Key Words: Shear bond strength, orthodontic bracket, hydrofluoric acid, orthophosphoric acid, maleic acid, sandblasting

I. INTRODUCTION

Adult orthodontic patients present most of the times with crowns or bridges. Bonding an orthodontic brackets to the porcelain face is a challenge and has a risk of deboning. Most of adult patients having different restorative treatments (fillings or crowns), orthodontists often face a significant challenge when bonding an orthodontic metal bracket to a porcelain surface [1].

Since porcelain surface is essentially inert and does not readily adhere to other materials, multiple approaches have been tried to alter the surface characteristics of porcelain or ceramic to provide sufficient bond strength to allow for the placement of orthodontic brackets [2].

Ideally, bonding a bracket to any surface must ensure an attachment withstand occlusal and orthodontic forces without dislodgment or breakage. However, be safe enough to avoid surface damage during debonding at the end of the proposed treatment [3].

To carry out orthodontic treatment, the ideal tensile bond strength of metal brackets to tooth structure is approximately 6 MPa to 8 Mpa [4].

Therefore, the bond strength of brackets to the surface should not exceed the upper limit. They are making this one of the biggest challenges faced by orthodontists if they decide to place the orthodontic bracket on a restored surface.

To achieve clinically appropriate bond strength when bonding orthodontic brackets to porcelain surfaces, the inert characteristics of the surface must be changed. This can be done either manually or by increasing the roughness of the porcelain base. Example either by micro-etching or the use of strong etchants such as hydrofluoric acid (or both), together with a silane coupling agent.

Chemical alteration of the porcelain surface can be done either by etching the surface to increase the mechanical retention of the adhesive or by changing the porcelain surface affinity to the adhesive materials.

Etching the surface: Hydrofluoric acid has been used successfully to etch the porcelain surface (glassy ceramics). Studies have shown that it significantly increases the bond strength of orthodontic attachments [5], [6]. However, one of the drawbacks of this approach is that the ceramic surface loses its glaze and becomes difficult for the clinician to restore its original luster.

Phosphoric acid have been used to etch porcelain surfaces because it does not cause as much damage as hydrofluoric acid [5]. However, it was found not as effective in providing adequate and consistent bond strength for orthodontic purposes.

Augmenting the bond strength to porcelain surfaces is by altering the nature of the surface by using a coupling agent such as silane [5]–[8]. Adhesion promoters, such as silanes, work by absorbing onto and modifying the surface of solid material via a chemical or physical process, allowing for increased adhesion to other materials [9].

Investigators have found that the silane coupler forms a chemical bond with both the resin and the porcelain, creating a bridge between the two materials [9], [10].

II. BACKGROUND

Orthodontic brackets are manufactured from various materials with different roughness, including ceramic, composite, plastic, metal, and titanium [11]. Among these various brackets, the most used type in the industry is the metal brackets, which are also the oldest [12].

Also, Brusca et al. mentioned that ceramic brackets could accumulate more bacteria than metal brackets [13].

Brackets are found in a selection of different designs. The designs can differ depending on the material from which the bracket is made, the base design, the base size, or the ligation [14], [15]. According to research, base design can influence the bonding strength of enamel. Mesh base design is the most used type of base design in the market [16].

Many other bracket base designs are available such as beaded with rounded pits and grooved base design [17].

Hydrofluoric acid: (HFA), also known as Hydrogen fluoride, is a chemical compound found in liquid or gas. The Molecular formula is H.F.

It has a powerful smell and can lead to severe burns, and is classified as a dangerous substance (PubChem, 2004a). The etching process with hydrofluoric acid can produce good bonding strength; on the other hand, it can lead to hazardous acid burns [18]. It is used as an etching solvent for dental ceramics [19].

Going back in history, in 1771, a Swedish chemist by the name of Carl Wilhelm Scheele discovered HFA when he was studying the mineral fluorite. HFA is a powerful dehydrating agent that is used in many industrial fields, such as the production of aluminium and stainless steel, glass etching, mineral processing, and much more [20]. Hydrofluoric acid manufacturing is done by combining fluorite with concentrated sulfuric acid at temperatures of 265 degrees Fahrenheit [21].

Some of the well-known hydrofluoric acid brands and manufacturers include IPS Ceramic Etching Gel, Ivoclar Vivadent (4% HFA), VITA CERAMICS ETCH, VITA Zahnfabrik (5% HFA and 10% sulfuric acid), Porcelain Etch, Ultradent (9% HFA) and PORCELAIN ETCHANT, Bisco (which can come in 2 different concentrations 9.5% or 4%) [22].

Regarding the use of hydrofluoric acid nowadays, the golden standard for etching lithium disilicate glass-ceramics is done by hydrofluoric acid. This acid etch procedure has been widely known when the etching of ceramics is required [23]. HFA can produce good bonding attributed to its roughing effect on the porcelain surface, leading to the high retention of resin composites (Lung and Matinlinna, 2012) [24]. HFA targets the silica phase leading to good bonding strength [25].

Hydrofluoric acid can penetrate the cells and destroy their metabolism leading to the death of these cells, and this why care should be taken when HFA is used for procedures in the oral cavity [26].

According to research, hydrofluoric acid is the favoured acid to etch the internal surfaces of ceramic restorations. The recommended etching time of ceramic is 23 min with 5% hydrofluoric acid, which results in a porous surface of the ceramic that allows the penetration of the resin [27]. An earlier systematic review stated that etching with HFA 9.6% is the best protocol [28]. Because of the HFA danger, acidulated phosphate fluoride (APF) in 1.23% concentration can replace HFA.

Orthophosphoric Acid: (OPA) is an inorganic acid that does not have any smell or colour. Its Molecular formula is H_3PO_4 orH_3O_4P.

Orthophosphoric acid is widely known to be used as an etching solvent for roughing areas where orthodontic brackets or fillings are to be placed (PubChem, 2004b).

Historically, in 1955 Buonocore invented the acid etching method, this method allowed bonding enamel to composites. He discovered that resin could be bonded to enamel after etching it with 85% phosphoric acid for 30 seconds [29]. Nowadays, the most widely used etching solutions have 30% to 40% phosphoric acid. This acid makes the enamel surfaces rougher and allows them to bond better [30].

In 1977 Fusayama et al. introduced etching by 40% phosphoric acid for both enamel and the dentin and then bonding them with phenyl phosphate to improve the bond strength [31]. Nowadays, the standard protocol for etching enamel is suggested to be from 35% to 37% orthophosphoric acid for 15 to 20 seconds [32].

OPA etching produces rough and high-energy surfaces on the tooth structure, the porous surfaces that the phosphoric acid makes lead to excellent micromechanical retention. This micromechanical retention is not as strong as the one created by hydrofluoric acid. On the other hand, since phosphoric acid is not as harmful or corrosive as hydrofluoric acid, it can be a suitable replacement for etching ceramic surfaces [33]. Besides, 37% phosphoric acid can be used to etch porcelain surfaces since it is less harmful to tissues and does not remove the glaze on the porcelain surface [34].

According to Silverstone, etching with OPA creates a porous and an etched zone [35]. During etching techniques, 32-37% phosphoric acid is utilized to uncover the collagen fibril network to better bonding composite resins [36]. Based on clinical trials, the performance of self-etch adhesives was enhanced after applying phosphoric acid to enamel surfaces. So, phosphoric acid has become the most widely used etchant when self-etch adhesives are used as well [37].

Maleic acid or cis-butenedioic acid is an organic compound with a dicarboxylic acid, a molecule with two carboxyl groups. Its chemical formula is $HO_2CCH = CHCO_2H$.

Maleic acid is the cis-isomer of butenedioic acid, whereas fumaric acid is the trans-isomer. It is mainly used as a precursor to fumaric acid, and relative to its parent maleic anhydride, maleic acid has few applications.

In the 1920's Maleic acid was very difficult to obtain, and thus its use was discouraged. However, Floyd was one of the first chemists to transform Fumaric acid to Maleic acid. He started by heating fumaric acid and diluted soda solution at $100\deg$ for 100 hours to finally obtain Maleic acid. In addition, he has also stated that Maleic acid is uncontrollable, inactive in moist environments and can decompose into the water at 200 degrees. A small amount of water is converted to Fumaric acid when heated in a sealed tube at $180\deg$ [38]. Moreover, now we find Maleic acid as a colourless, crystalline organic compound used to make other valuable chemicals; it also replaced formaldehyde-based dimethylol dihydroxy ethylene urea anticrease for cotton fabric.

In Dentistry, Maleic acid is an effective irrigant solution used to remove the smear layer. It can significantly decrease dentin microhardness by demineralization and softening it through its chelating agent. This effect was proven while comparing "The effect of Maleic acid and EDTA on the microhardness and surface roughness of human root canal dentin [39]. One of the main clinical concerns in orthodontics is the bonding and debonding of the brackets used, which over time will damage the enamel surface. However, it is important to know that 10% maleic acid gel for 15 and 60 seconds produced similar micromorphological effects on the dentin surface [40]. But no evident morphological differences were observed in the type of enamel etching patterns when treated with 10% maleic acid gel for 15 and 60 seconds [40].

Moreover, in orthodontics, Maleic anhydride gets converted to maleic acid when it is exposed to a moist environment during the cementation of brackets. Thus, the mechanical properties in resin cement containing maleic anhydride may be affected negatively due to long term water storage [41].

Macroetching is achieved by Air abrasion, also called sandblasting. It has considerable significance in mechanical resistance adhesion [42]. Studies have shown that the application of air abrasion with aluminium oxide increases the surface, thus providing a more convenient adhesion [43]. Sandblasting technique was first introduced by Benny Chew Tilghman in 1870; back then, it was used to sharpen tools, engraving and cleaning and then in 1951, Robert Black officially introduced it to the field of dentistry; however, it was not easy to catch on to because it was not compatible with filling materials such as amalgam and gold and did not show promising results thus, it did not gain popularity back then.

However, after the development of bonding, restorative and isolation materials, the rebirth of air abrasion came back to the field. Air abrasion is a pseudo mechanical method to remove and dentinal hard tissue [44]. Studies have proven that the bonding of both enamel and dentin surfaces showed better results when prepared with air abrasion than traditional carbide burs or etching [45]. Moreover, Sandblasting has the advantage of decreasing noise and vibration compared to conventional rotary instruments, thus having more patient comfort [46]. Regarding materials used, aluminium oxide, also known as alumina, are the most currently used and the most abrasive type of air abrasion; however, even though it is the most used, it showed some side effects such as microcracks or large cracks shown by the CAD/CAM while composite was used as a sample [47]. Up until this date, the use of bands in orthodontics was never diminished. In 1996 researchers studied the effect of sandblasting on orthodontic bands and concluded that, sandblasting the surface of a stainless steel band doubled the retention strength of the cement used. Thus we understand that sandblasting increases the surface area and has a thinning effect on the oxide layer of the stainless steel band [48]. In another in-vitro study, the probability of bond survival with sandblasting was greater than the non-sandblasted ones with a strength of 1.76 Mpa comparing to 1.66 Mpa when using 35% phosphoric acid gel for 30 seconds [49].

The purpose of this study is to report on the different approaches taken to improve the bonding of orthodontic brackets to porcelain surfaces and to review the literature and test the available alternatives of hydrofluoric acid used for that purpose.

III. MATERIAL AND METHODS

This is a pilot study carried out at Ajman University Orthodontic Research Lab. For this study, a variety of resources were used to obtain our results, including: The searched engine was PubMed, Scopus, Google Scholar and Science Direct. Eighteen porcelain fused to metal crowns fabricated at Ajman University Prosthodontic Lab. Acrylic tooth holder fabricated at Ajman University Prosthodontic Lab (Figure 1).

The etchant used in the study were Hydrofluoric acid 9.6% from Dental Care Plus, manufactured in the USA, (Figure 2A); Orthophosphoric acid 37% from Lancer Orthodontics, manufactured in the USA, (Figure 2B) and the Maleic acid 10, 20, 30% from Sigma Aldrich, manufactured in the USA (Figure 2C).

High speed handpiece; NSK, manufactured in Japan and a round bur 2.3mm, manufactured in the USA (Figure 3).

Bonding agent (American Orthodontics MTP Primer, manufactured in the USA), composite (American Orthodontics Medium Viscosity Adhesive, manufactured in the USA), mini master maxillary left central bracket (American Or-

FIGURE 1: The porcelain crowns with the model holder

FIGURE 2: A: Hydrofluoric acid, B: Orthodphosphoric acid, C: Maleic acid

FIGURE 3: Roughening the porcelain surface

FIGURE 4: Bonding agent, microbrush, bracket, bracket holder, Composite, light cure

FIGURE 5: Universal Testing Machine (UTM)

thodontics, manufactured in Sheboygan, Wisconsin, USA), bracket holder a light cure (Acteon Satelec, manufactured in France) (Figure 4).

Universal Testing Machine, Testometric M350-5CT, manufactured in the United Kingdom (Figure 5), and the images were captured using iPhone Xs Max (Figure 5) .

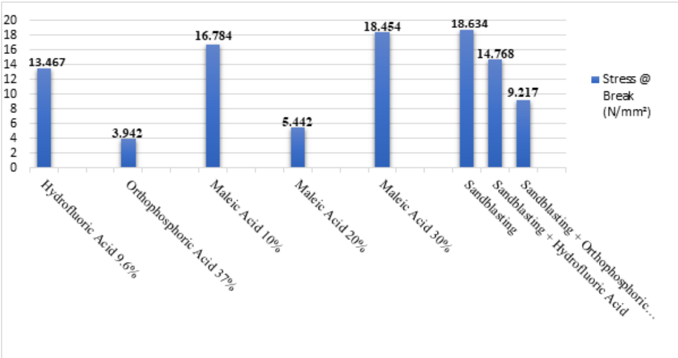

FIGURE 6: Shear strength / one minute

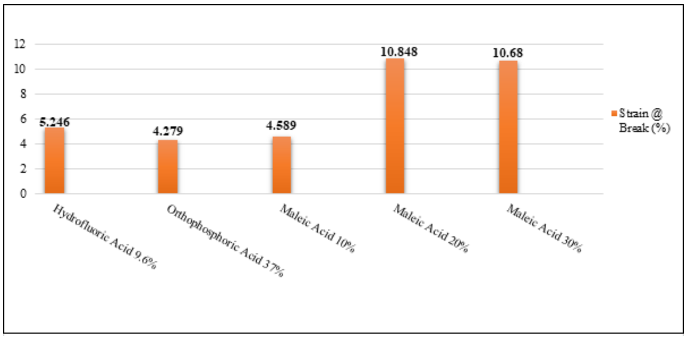

FIGURE 7: Shear strength at 2 minutes

IV. RESULTS

This study is a pilot study that consisted of 18 PFM crowns and the use of different acids. The acids used were Hydrofluoric Acid 9.6%, Orthophosphoric Acid 37%, Maleic Acid 10%, 20% and 30%, sandblasting using a high-speed handpiece and a round bur (Table 1). All results were obtained using the Universal Testing Machine (Figure 5).

A. RESULTS AT 1 MINUTE

Sandblasting on its own showed the highest results amongst all etchants and its variables. Maleic acid 30% were found to have the highest shear strength amongst all three concentrations and other acids.

Orthophosphoric Acid 37% showed the weakest result in comparison to the other acids and sandblasting technique (Figure 6).

B. RESULTS AT 2 MINUTES

Maleic Acid 20% showed the highest result in comparison to the 3 concentrations and other acids. Orthophosphoric Acid 37% showed the weakest result in comparison to the other acids.

No sandblasting with acids was done for the 2-minute interval (Figure 7).

C. RESULTS AT 3 MINUTES

Orthophosphoric Acid 37% showed the highest shear strength in comparison to the other acids.

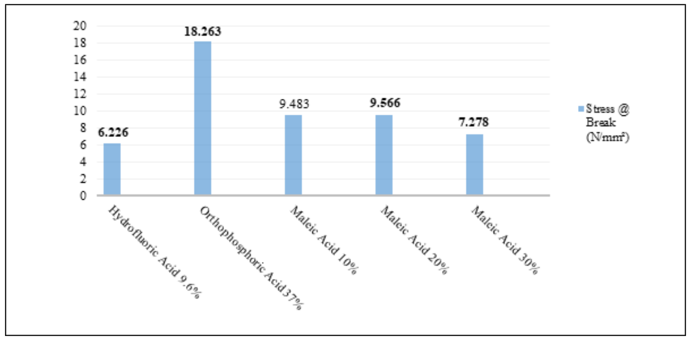

FIGURE 8: Shear strength at 3 minutes

Hydrofluoric Acid 9.6% showed the weakest strength in comparison to the other acids. No sandblasting with acids was done for the 3-minute interval (Figure 8).

V. DISCUSSION

Bonding orthodontic brackets to glazed surfaces like porcelain require different surface etching or conditioning types than the natural tooth surface. This is credited to the ability of the adhesive to penetrate the surface of the etched natural tooth to form what is known as resin tags. This process, however, does not take place in many materials, including porcelain [50].

This study assessed several surface etching and roughing techniques for porcelain surface before orthodontic bracket bonding. We tested their shear bond strength (SBS) at debonding from the porcelain surface. In this present study, the SBS values at 1 min of etching the porcelain surface were the highest for Maleic acid 30%, with the value of (18.454 N/mm^2). However, not enough studies were available to compare SBS values after etching with Maleic acid 30% for 1 min.

In addition, the highest shear bond strength value obtained in our study after etching for 2 mins with several acids of different concentrations is (10.848 N/mm^2) for Maleic acid 20%, showing a lower shear strength compared to Maleic acid 30% etching for 1 min.

In comparing Hydrofluoric acid and Orthophosphoric acid in our study, we note that Hydrofluoric acid has a higher shear strength than Orthophosphoric acid when used for etching at 1 minute and 2 minutes. Moreover, a study done in Brazil by Stella et al. had (22.83 MPa or N/mm^2) results after etching with 10% Hydrofluoric acid for 1 minute and a result (16.42 MPa or N/mm^2) after etching with 37% Orthophosphoric acid for 1 min. However, it was noted that even though Hydrofluoric acid had an excellent shear strength, it caused a high surface damage rate to the porcelain surface. In contrast, Orthophosphoric acid caused minor damage to the surface [50].

In another study by Yassaei et al. in 2013, etching by 9.6% Hydrofluoric acid for 2 minutes was done, and a result of (7.4 MPa or N/mm^2) was obtained. Our study resulted from (5.246 N/mm^2) was obtained for the same variables [51].

Description		Etching/minutes	Stress @ Break (N/mm^2)
Hydrofluoric acid 9.6%		1	13.467
		2	5.246
		3	6.226
Orthophosphoric acid 37%		1	3.942
		2	4.279
		3	18.263
Maleic acid	10%	1	16.784
		2	4.589
		3	9.483
	20%	1	5.442
		2	10.848
		3	9.566
	30%	1	18.454
		2	10.68
		3	7.278
Sandblasting		No etching	18.634
Sandblasting + Hydrofluoric acid		1 minute	14.768
Sandblasting + Orthophosphoric acid		1 minute	9.217
Sandblasting + Maleic acid		1 minute	

TABLE 1: Summary of the findings

According to Kurt et al. in 2019, the shear bond strength results obtained after etching with 9.6% Hydrofluoric acid for 2 min on felspathic porcelain were (8.84 N/mm^2) [52].

On the other hand, we noted that the highest shear strength detected in our study after etching with different acids for 3 minutes was for Orthophosphoric acid 37%, which had a value (18.263 N/mm^2). In our study, sandblasting using a round diamond bur and high-speed handpiece was performed on porcelain fused to metal (PFM) crowns. We concluded that sandblasting has the highest shear bond strength of (18.634 N/mm^2).

While a study that Alaku Sabuncuoglu and Erturk in 2016 showed that the mean shear bond strength of sandblasting with diamond bur was (3.498 N/mm^2). Indicating that our study showed a significant difference in values of shear strength from the other research when sandblasting alone was involved. Furthermore, Orthophosphoric acid 37% was used to etch the porcelain fused to the metal surface for 1 minute after sandblasting, concluding that (9.217 N/mm^2) was the average shear strength. While in the study done by Alaku Sabuncuoglu and Erturk, which included etching with Orthophosphoric Acid 37% for 2 minutes after sandblasting, showed average shear strength results (6.182 N/mm^2).

Hydrofluoric Acid 9.6% was applied on the porcelain fused to the metal surface for 1 minute after sandblasting and showed shear strength (14.768 N/mm^2). However, in comparison to the study done by Alaku Sabuncuoglu and Erturk that included etching with Hydrofluoric Acid 9.6% after sandblasting with diamond bur for 2 minutes concluded that the average shear strength was (11.19 N/mm^2).18 Whitlock et al. and other studies suggested that the recommended values for shear bond strength for an orthodontic bracket should be between (6 to 8 Mpa or N/mm^2). These values are strong enough to maintain the attachments to the surface throughout time. Still, they can also be weak to maintain the integrity of the porcelain surface after debonding the bracket [53]. A recent literature review study that was done by Alzainal et al. in 2020 called "Orthodontic Bonding: Review of the Literature" concluded that the values of (6-8 Mpa or N/mm^2) should not be utilized as a reference for shear strength because it is not clear how the values became regarded as the recommended values of shear bond strength that the orthodontic bracket is exposed to [54].

The same article also mentioned that the golden method of conditioning ceramics is 9.6% hydrofluoric acid etching. The same authors also noted that 5% hydrofluoric acid could be used on ceramics too. However, hydrofluoric acid etching intraorally can be dangerous as it is considered toxic. Hydrofluoric acid aalternatives like orthophosphoric acid, sandblasting, and CO2 laser can be used instead [54].

VI. CONCLUSION

Based on the result obtained fro our research, we could conclude could conclude that the use of sandblasting technique without etching has shown the strongest result with a shear strength of 18.63N/mm. Moreover, the use of Maleic acid 30% for 1 minute showed a shear strength value of 18.45N/mm.

In Addition, etching with Orthophosphoric acid 37% for 3 minutes showed a shear strength value of 18.26N/mm, which also is very promising.

On the contrary, etching with Orthophosphoric acid 37% has shown the lowest shear strength value at 1 minute, 3.94N/mm. However, at 2 minutes, Orthophosphoric acid 37% resulted in a higher shear strength which was 4.27N/mm. Nevertheless, maleic acid 20% at 1 minute in a weak shear strength 5.44N/mm.

Based on these considerations and results, we can acknowledge that every acid has a different shear strength value dependent on the concentration and the etching time used on the subjected surface. In conclusion, the use of maleic acid lacks sufficient research but showed promising results that could be further studied to establish its appropriate use in dentistry as a surface conditioning agent and its role in bonding orthodontic brackets.

RECOMMENDATIONS

We recommend further advanced studies in regards to our reference findings. We advise using a more significant sample and a comparison on extracted natural human teeth to assess the effect of these acids and the timing of etchant. We also recommend manufacturers experiment further with Maleic acid under different time intervals to assess its benefits to bonding to a Porcelain surface and human teeth.

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CONFLICTS OF INTEREST

No conflicts of interest have been declared by the authors.

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