Effect of fiber on the fracture strength of implant-cement interfaces

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Abstract:

The interfacial mechanics at the implant-cement interfaces is a critical issue for implant fixation and the filling of tissue defects created by disease. Early loosening and failure of implants have been issues in medical field today. Electrospinning is a process by which fibers with sub-micron diameters can be obtained from an electrostatically driven jet of polymer solution. These fibers have a high surface area to volume ratio, which have numerous interface tissue engineering applications. The present study is based on the hypothesis that the differences of the surface properties at titanium/cement interface due to incorporation of micro and sub-micron diameters fiber may have significant influence on the quality of titanium/cement union. The objectives of this research is to design and construct electrospinning unit for the fabrication unidirectional and bidirectional Polycaprolactone (PCL) fiber and to measure the interface fracture strengths of sandwiched titanium and cement samples with uni- and bi-direction fibers at the interface under tension, shear and mixed forces. The next objective is to then apply the fibers on a titanium rod and test the strength under cyclic loading. Both uni- and bi- direction fibers were collected on carbon tape and Ti for Scanning electron microscope (SEM) imaging of the fibers and interface fracture experiments, respectively. Titanium (Ti) and poly methyl methacrylate (PMMA) cement sandwiched specimen were prepared. The tension, shear and mixed tests were conducted on Ti/PMMA using Evex tensile test system. The experiment found that the interface fracture toughness of all different kinds of sandwiched Ti/PMMA samples with fibers was significantly higher than the respective sandwiched Ti/PMMA samples without fibers.

Background:

Electrospinning is the process of producing fibers in the range of micro to nano scale using polymer solution [1]. These micro to nano fibers from the electrospinning has many applications in a diverse range of fields, such as biomedical engineering, filtration, electrical engineering, and optics [2]. In the biomedical field, the studies of joint replacement show that loosening of the implant from the bone-cement is the first mechanical event of loosening [3]. Loosening can occur due to unsustainable interface stresses, usually initiated from defects along the interface [4]. The use of the electrostatic fiber in the field of biomedical industry has been increasing rapidly recently. The fibers are being used in the medical field for improving surface properties of implants [5]. In this study, experiment was performed to analyze the differences of the surface properties at titanium/ cement interface due to incorporation of micro and sub-micron diameters. This study hypothesized that fiber pattern and loading directions may have significant influence on the quality of titanium/cement union.

Materials and Methods:

Design and manufacture of the setup:

PCL fiber was used because of ease of fiber fabrication, biocompatibility and cost. PCL beads were dissolved in acetone with concentrations varying from 6-15 wt.% using sonicator. The sonication process was carried out at approximately 80°C for 5 hours. Viscosity of the solution was measured using Malvern CVO rheometer to record wt% of PCL and viscosity relation.

To produce unidirectional aligned fiber, vertical drum extraction method was used. Fig 1 shows the vertical setup for the electrospinning process. The distance between the syringe needle and the collector was fixed at 20 cm. However, the speed and the applied voltage was changed to obtain the fine fiber. A DC motor was mounted on a Newport linear stage and the motion of stage was controlled by Newport actuator and motion controller. Fig 2 shows the unidirectional fiber on the titanium plate collected during the experiment.

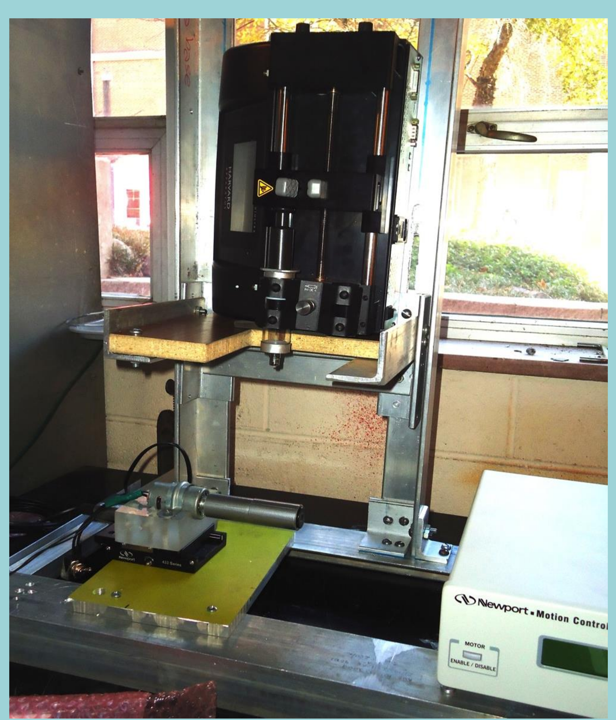

Fig 1. Electrospin setup.

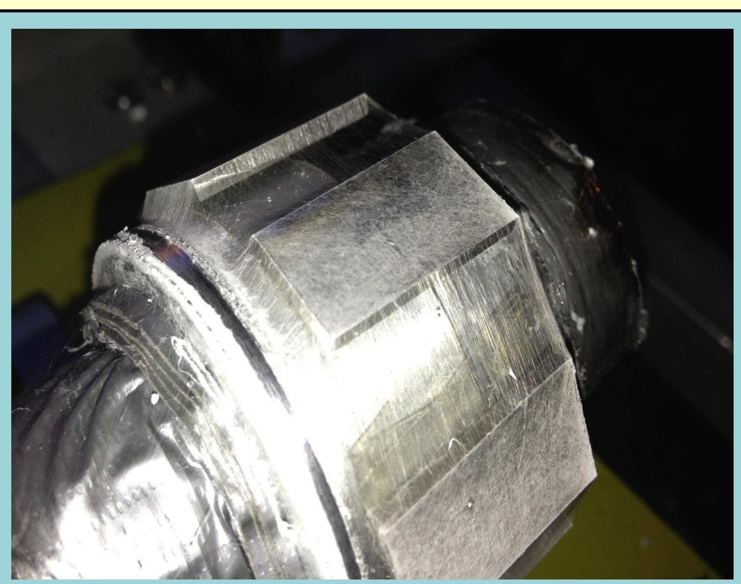

Fig 2. Uni-direction fiber deposition on Ti plates

To produce bi-directional aligned fiber, vertical method was used as well. Two sets parallel plates were mounted on an acrylic. Ti plates were placed in between the parallel plates. Two parallel plates were charged in different time period which will change the direction of the collected fiber on Ti as shown in the Fig 3.

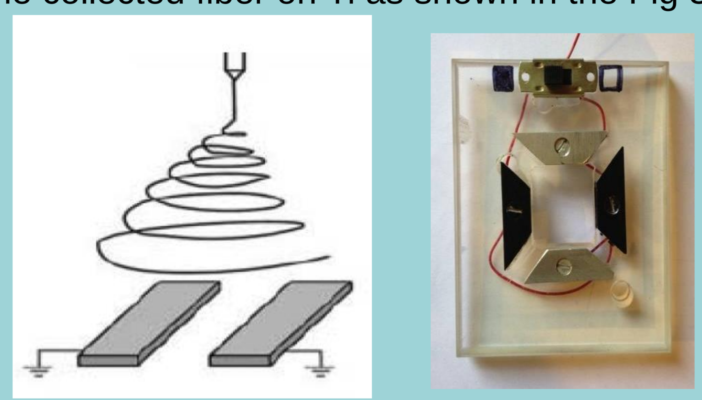

Fig 3. (a) Schematic representation of parallel ground plate method for fabrication of bidirectional fiber (b) Fabricated alternative charge ground plate for deposition of bidirectional fiber on Ti plate.

Cobalt™ HV bone cement , a commercial orthopedic bone cement, was used in this research as PMMA bone cement. PMMA beads were mixed with MMA monomer to prepare the cement using solid:liquid ratio 2:1. PMMA is cured on different Ti plates in a custom made mold. Evex tension stage was used to find the interface fracture toughness of Ti/PMMA sample, which is discussed in detail in *Khandaker et. al.* [6].

Experiment Design Process:

Fig. 4 shows the flowchart of the experiment design process to evaluate the objectives:

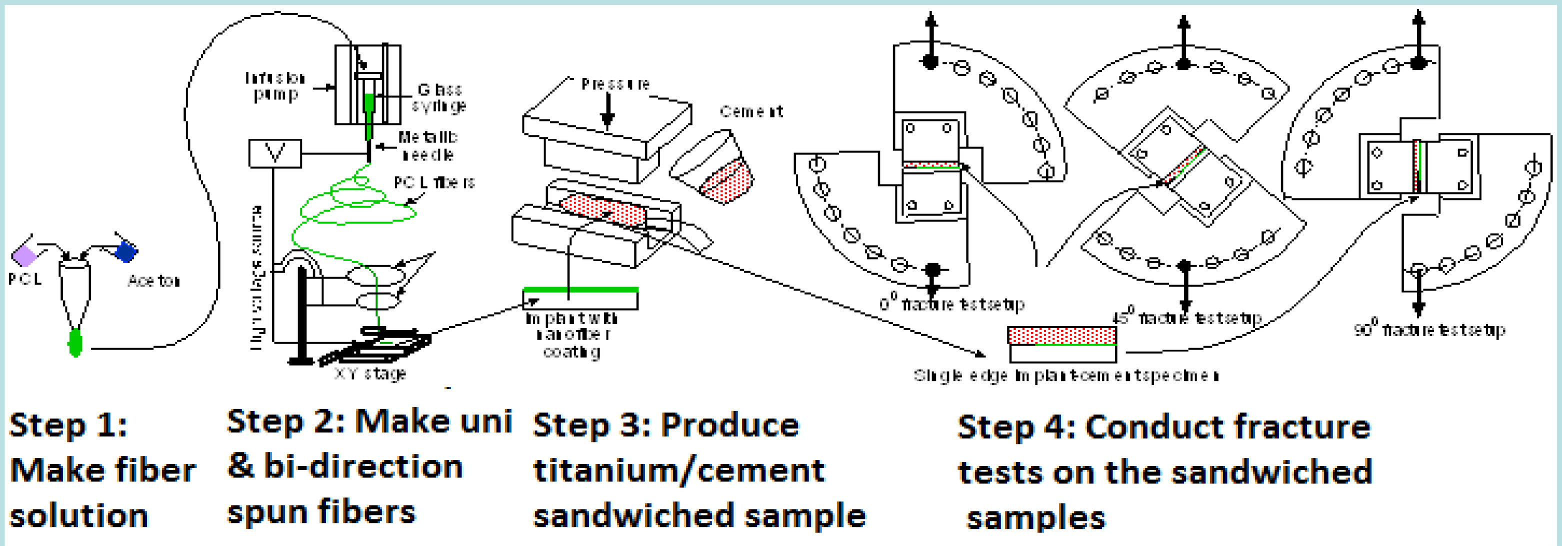

Fig 4. Schematic view of the overall design process starting of the experiment.

Future Testing

The next step for testing, currently underway, is the cyclic loading test using the pull-out method. This is the same idea as the sandwiched samples only applied to a cylindrical rod tested under fatigue loading on a test recourses tensile/compression tester. The fatigue test is performed on both fibreless and fibered specimens. With the fatigue pull-out method a system had to be developed in order to conduct the test in a simple and efficient way. This was accomplished by making the mechanism in Fig 5. The mechanism allowed for two obstacles to be overcome at once. The first being a way to vertically fix the rod while curing took place while the second obstacle was to keep the fixed rod vertical while applying the required load for curing.

Fig 5. device for fatigue test samples.

Results:

The relation between wt% of PCL in fiber solution and viscosity of the sonicated solution is shown in Fig. 6. There is an increase of viscosity was found with the increase of wt% of PCL in the polymer solution. Uni-and bi- direction PCL fibers were successfully produced using the electrospun unit as shown in Fig 7. Diameter of produced fibers was found to be in the range of 919 nm – 1.25 µm as shown in Fig 6.

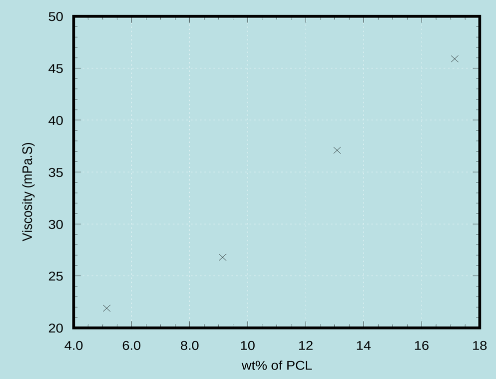

Fig 6. Relation between wt % PCL and viscosity of fiber solution

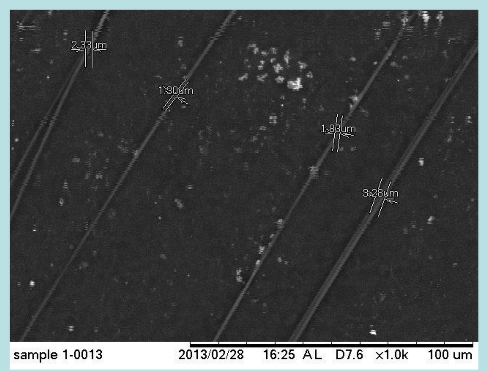

Fig 7. SEM image of uni-direction fiber at 1000x magnification

Figures in 8 show the three different kinds of fabricated test setup using Evex micro mechanical tester to conduct tension, shear and mixed loading fracture tests on different kinds of Ti/PMMA samples.

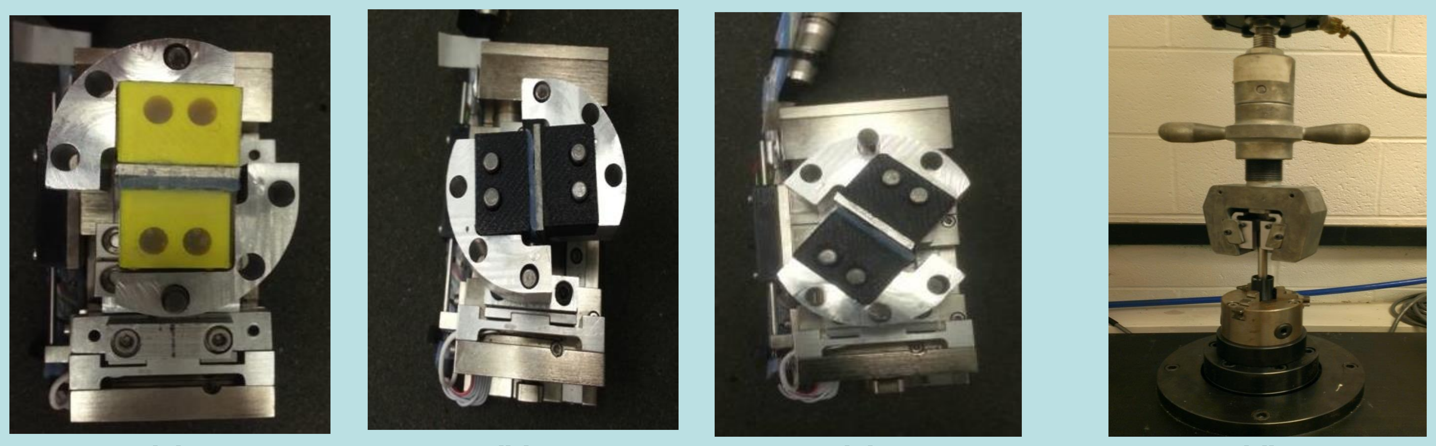

Fig 8 Mechanical tests on Ti/PMMA samples under (a) tension (b) shear (c) mixed loading (d) fatigue

Fig. 9 shows that interface fracture toughness, K_{IC} of Ti/PMMA samples with unidirectional fibers is higher than Ti/PMMA samples without fiber under tension load. Results show that fiber pattern (uni- or bi-directions) in Ti/PMMA samples have no significant influence on the K_{IC} values of those Ti/PMMA samples.

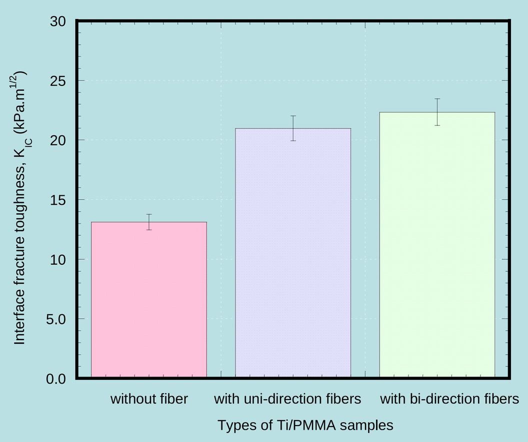

Fig 9 Tension tests on Ti/PMMA samples: without fiber, with uni-direction, and bi-direction fibers

Fig 10 shows the effect of loading on the interface fracture toughness of Ti/PMMA samples. Results show that the shear loading has higher influence in the interface fracture toughness of Ti/PMMA samples without fiber compare to the similar samples under tension and mixed loading. This result is in agreement with Mann *et al*. [7]. These authors found that mechanical strength of the cement bone interface is greater in shear than tension. Table 1 shows the comparison of interface fracture toughness for different groups of specimen tested in this study.

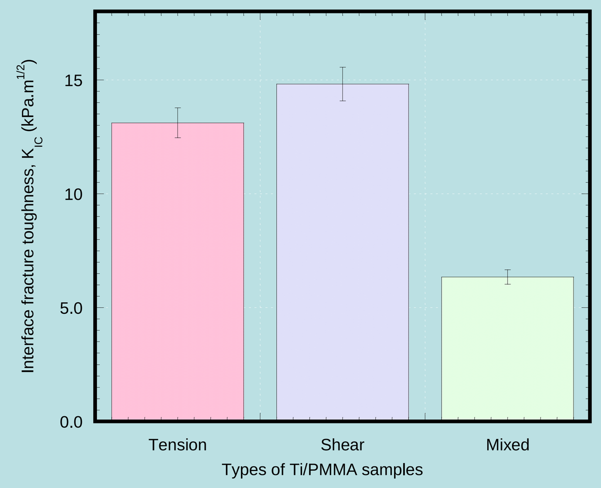

Fig 10 Mechanical tests on Ti/PMMA samples without fibers under tension, shear and mixed loading.

Table 1. Experimental response parameters for measurement of the effect of loading and fiber pattern on the interface loading of Ti/PMMA samples.

Description	Tension		Shear		Mixed	
	w/o fiber	w fiber	w/o fiber	w fiber	w/o fiber	w fiber
No of specimen	3	3	3	2	3	3
Average width, W (mm)	23.15 ± 0.30	21.7 ± 1.99	22.76 ± 0.41	22.75 ± 0.37	23.06 ± 0.27	23.13 ± 0.39
Average height, H (mm)	2.03 ± 0.00	1.89 ± 0.19	2.02 ± 0.00	2.02 ± 0.01	2.06 ± 0.06	2.03 ± 0.02
Average thickness, B (mm)	12.15 ± 0.11	11.17 ± 1.06	12.1 ± 0.03	11.93 ± 0.31	12.11 ± 0.03	12.16 ± 0.07
Average crack length, a (mm)	10.7 ± 0.89	7.19 ± 1.71	10.31 ± 0.28	9.65 ± 0.67	10.59 ± 0.13	10.06 ± 0.26
Interface fracture toughness, K_{IC} (KPa.m$^{1/2}$)	13.11 ± 1.72	20.98 ± 2.49	14.82 ± 1.32	20.95 ± 0.44	6.35 ± 1.83	12.71 ± 3.10

Conclusion:

Both unidirectional and bidirectional fibers were successfully prepared using the fabricated electrospin unit. Several Ti/cement were prepared to measure the effect of loading and fiber pattern on interface fracture toughness with and without fibers. The data shows that shear loading has higher influence on interface bonding of Ti/PMMA samples compare to sample under mixed and tensile loading. Similarly, Ti/PMMA samples with unidirectional fiber has higher interface bonding strength compare to samples without fibers. Test are continuing for effects of fatigue stress on titanium/PMMA both with and without fibers.

Acknowledgements:

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