Strength of interface in bioresorbable poly-lactic acid/Mg fiber composites for orthopedic applications

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Introduction

Challenges associated with conventional metallic orthopedic implants

- Higher stiffness as compared to human bone leading to bone diseases like osteoporosis.
- Second surgery to remove the non-degradable implant. Increases cost and, in majority cases, patients have limited movement after a second surgery for several months.
- Poor osteoconductive nature.
- Limitation in tailoring mechanical and biological properties of materials according to customized need of patient

"Bioresorbable materials can be an alternative solution"

Challenges associated with bioresorbable PLA polymer implants

- Low mechanical properties forcing implant size to increase and limiting its application areas.
- Prolonged degradation period larger than bone healing period.
- Degradation by-products can lead to inflammatory responses due to their acidic nature.

Challenges associated with bioresorbable Mg metallic implants

- Production of magnesium with best alloying and processing conditions.
- Rapid and unpredictable corrosion leading to unexpected failure of implant
- Degradation by-products can lead to inflammatory responses due to their basic nature.

"Bioresorbable polymer and metals can counter challenges posed by conventional metallic implants but they also pose new challenges which are intrinsic in their nature... And still unsolved!
Combining these two materials as composite can counter drawbacks of all above materials

Synergetic advantages of bioresorbable Magnesium and PLA composite

Property	Magnesium	PLA	Benefit as composite
Mechanical properties	Higher than bone	Much lower than bone	• Customization of mechanical by varying amount, size, and orientation of constituents.
			•
Resorption time	Short	Long	• Overall degradation time can be tailored. • PLAs degrade faster due to basic by-product and excess surface area around reinforcements. • Mg degrades slower as polymer matrix protects it from fast corrosion.
Degradation by-products nature	Basic	Acidic	• Neutralization can take place and pH around implant will not be changed drastically
Osteointegration	High	Very low	• An optimum osteointegration level can be achieved.
Drug loading potential	No	Possible	• Can not only be made possible but the way drug is stored and released can be customized

Missing piece of puzzle (Interfacial characterization)

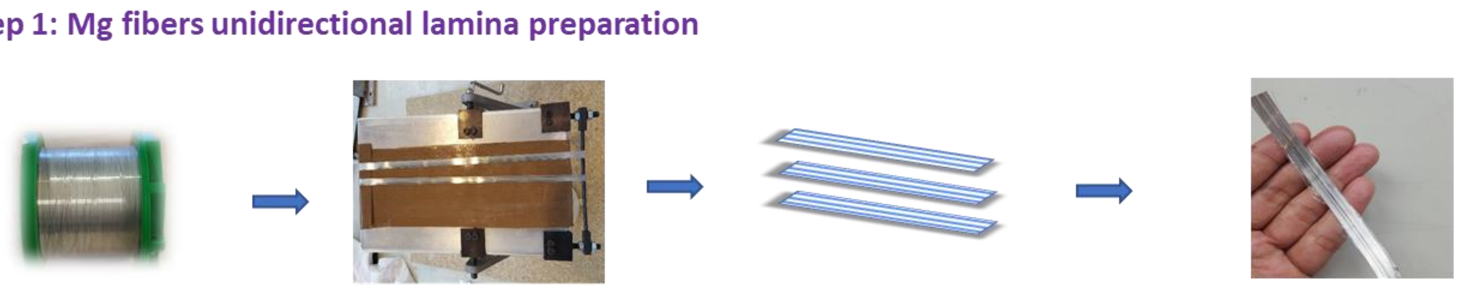
- There is no robust technique exploited for the characterization of interface of bioresorbable composites.
- This study propose the application of push-out test for Mg/PLA composites which can be helpful for optimum design of such implants

Material and methods

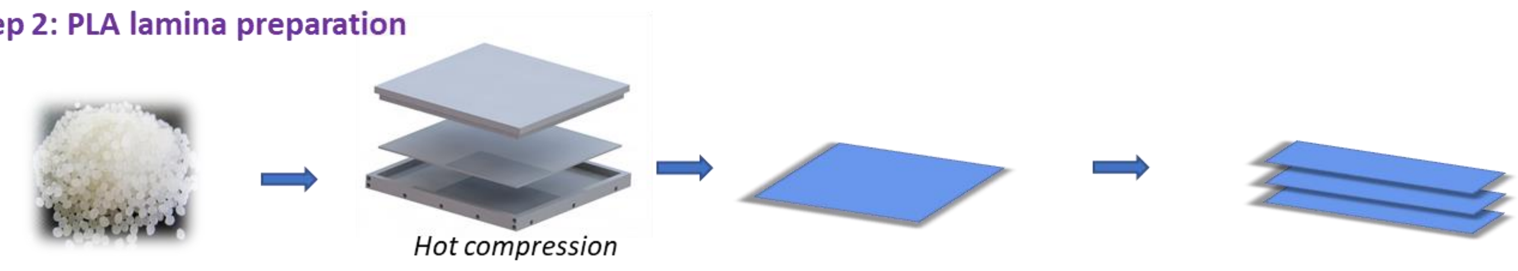
Mg/PLA Composite preparation process

- It is a three-step process where laminas of Mg fibers and PLA are prepared from raw materials in form of spool and pellets and compressed in hot mold as shown below schematically:

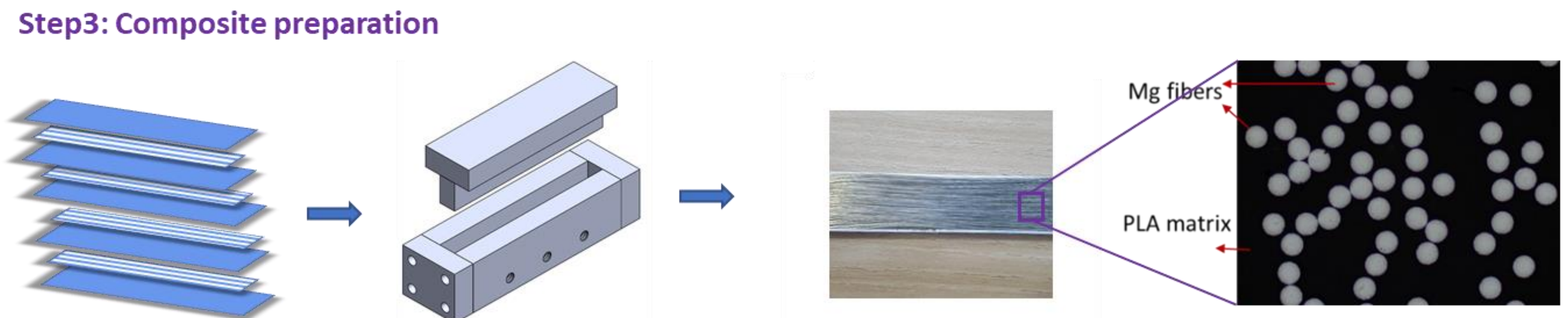
Step 1: Mg fibers unidirectional lamina preparation



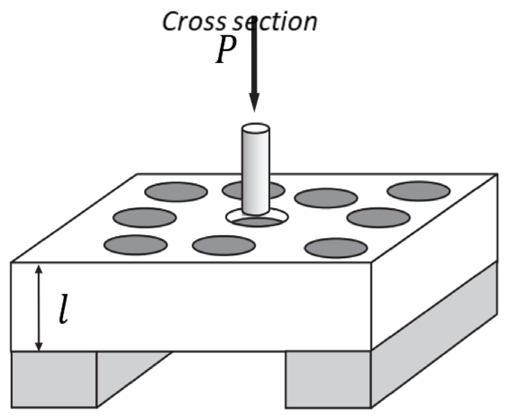
Step 2: PLA lamina preparation



Step3: Composite preparation



Nano-indentation technique of push-out test

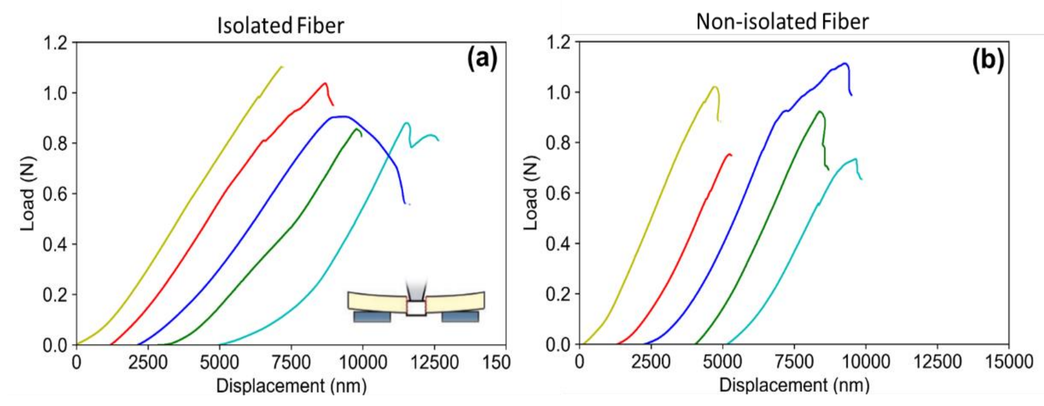


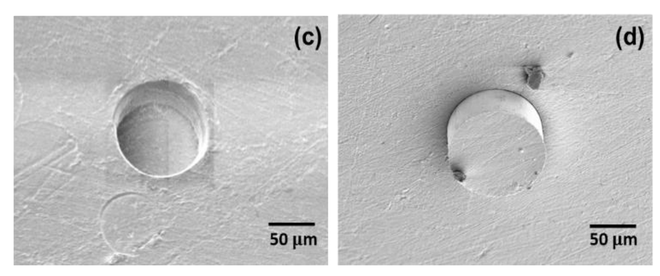
- It was used to the interfacial behavior of fiber/matrix
- Sample is prepared in form of thin slice of cross-section
- A single fiber is loaded with the help of indenter
- Two cases were considered a) isolated fiber and b) non-isolated fibers
- Interfacial shear strength is measured from following formula: $\tau = \frac{P_{max}}{2\pi Rl}$

Results

Load-displacement curves of Push-out test

- Initial slope corresponds to elastic bending of slice inside slot.
- Then curve became linear showing elastic response of interface.
- First point of non-linearity is the indication of crack initiation.
- The crack grows gradually and whole interface ruptured suddenly shown by sudden drop of force to zero in Fig (a).
- Fiber popped out from back shown in Fig (c) and (d).





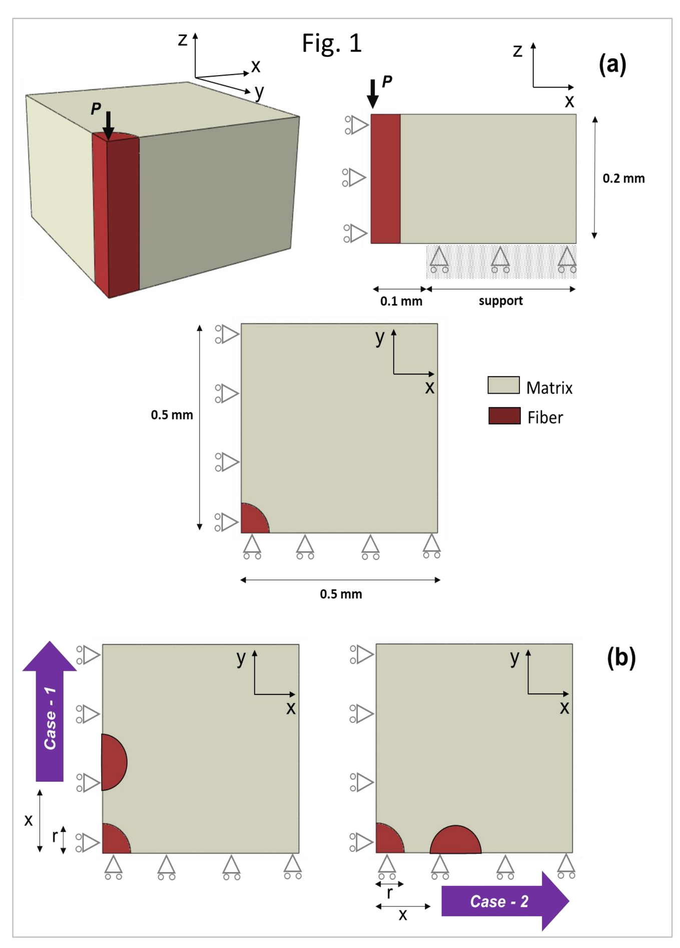
Effect of constraint fibers (when indented fiber has neighboring fibers)

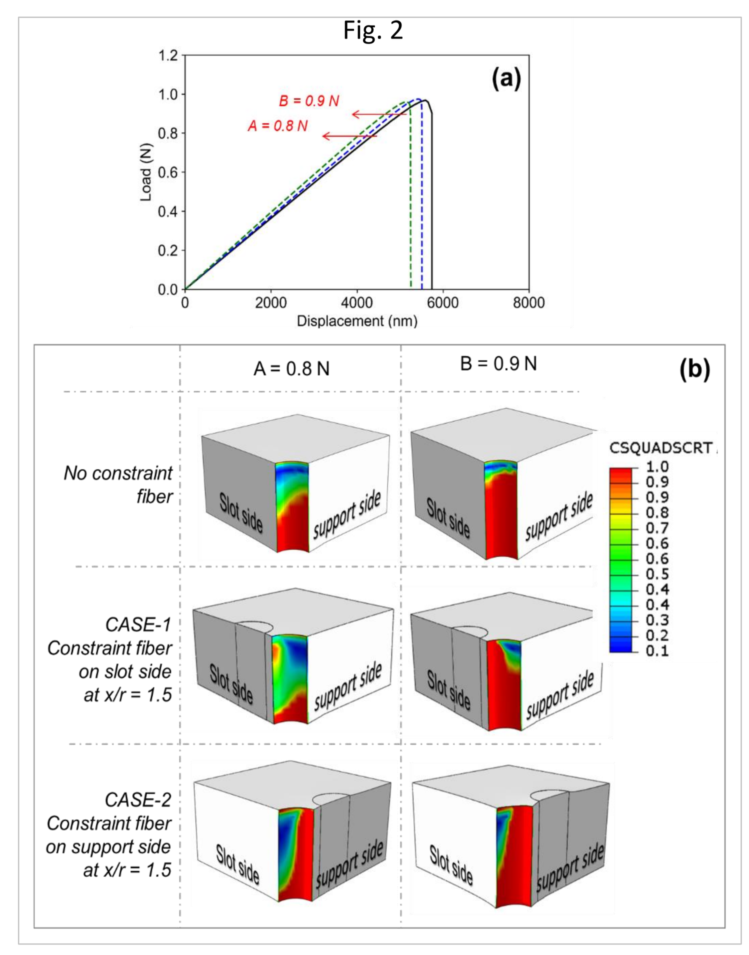
- Non-isolated fibers were also indented to check the effect of constraining fibers on the accuracy of push-out test . Fibers were randomly selected.
- The load-displacement curves are shown in above Fig. (b)
- The initial slope is higher while the overall behavior of curve and peak load is like the case of isolated fibers.
- The results of both scenarios are summarized in following table:

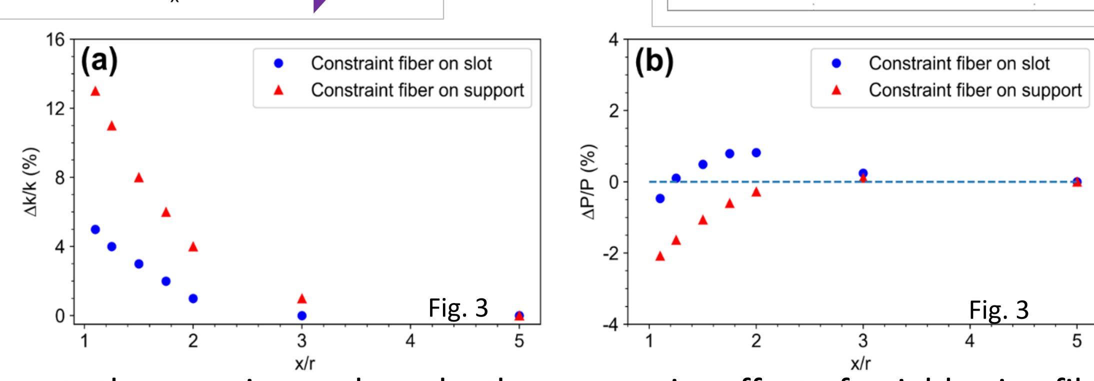
Scenario	Avg. Interfacial Shear Strength ISS (MPa)	Slope of linear region* (N/mm)
Isolated fiber	15.2 ± 1.5	200 ± 26
Non-isolated fiber	14.2 ± 2.6	268 ± 11

Quantification of constraint effect of neighboring fibers with the help of simulation

- The simulations of push-out test were carried out to study the onset of interfacial damage, shear stress distribution across interface, stresses in PLA matrix and influence of neighboring fiber in ABAQUS/CAE 2016.
- The interfacial behavior was modelled by cohesive contact interaction using linear traction-separation law.
- The description of simplified model is shown below. First parameters of cohesive contact were calibrated for experimental curve and then neighboring fibers were added first on slot side and then support side.
- Results for both cases are summarized below:







- The simulation supports the experimental results that constraint effect of neighboring fibers (non-isolated fiber) is **not significant** for both cases when the neighboring is on slot side or support side.
- The slope of linear region of force-displacement curve shown in Fig. 3a can show change of upto 12% error while the estimation in peak is not changed more than 2%.
- The damage progression as shown in Fig.2 is different for both cases.
- Constraint effect diminished when neighboring fiber is at distance of 3 times the radius

Conclusion

- Interfacial strength of Mg fiber and PLA is around **15 MPa**.
- The nature of interface is **brittle** as no friction is observed after peak load.
- **Effect of constraint fibers in not significant** highlighting the robustness of this method. Any fiber can be selected for push-out test

Acknowledgements

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