CIC 2025 Conference

4th Coatings and Interfaces Online Conference

21–23 May 2025 | Online

MDPI

High-power laser surface structuring of bioactive glasses: Recent advances and perspectives

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INTRODUCTION & AIM

Context: Bioactive glasses (BGs) are widely used for their **osteoconductive** and/or osteosynthesis **capabilities**, but **more stable compositions are needed**, especially for high surface/volume ratio applications, where reactive BGs dissolve too quickly.

Challenge. Surface micro-structuring is relatively unexplored, as osteoconductivity is linked to surface layer dissolution. However, **laser surface modification (LSM) can create permanent long-term surface patterns to improve biological interactions**, offering precision and control without toxic substances or mechanical stress.

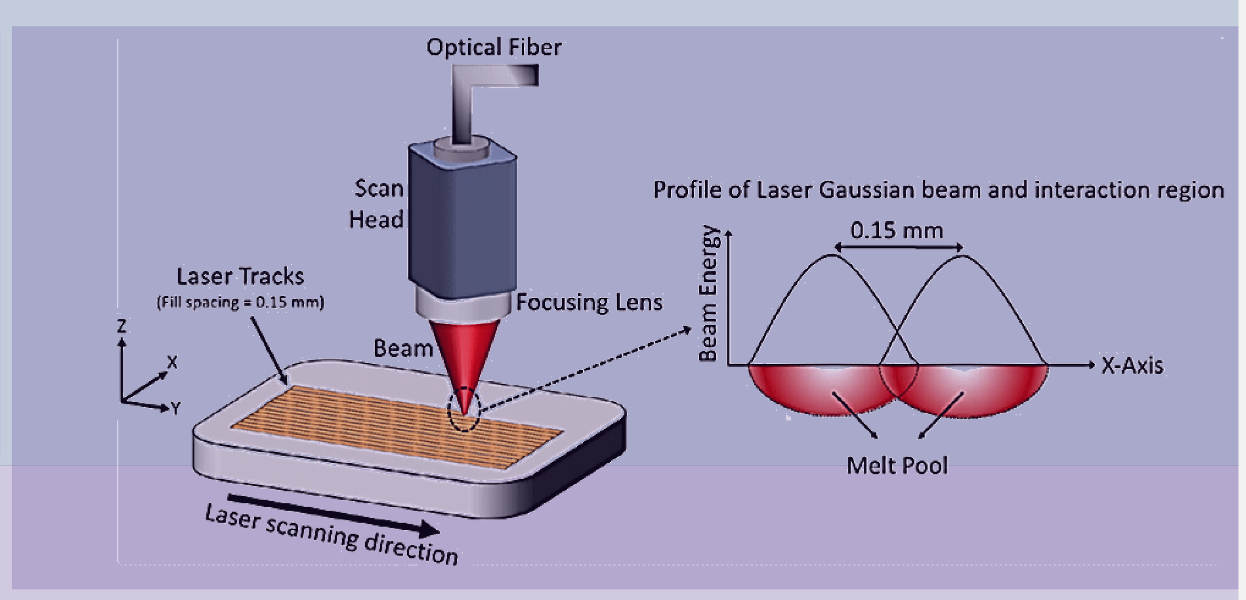
Problem. Melt-derived BGs (e.g., 45S5, ICIE16) while excellent for bone regeneration, **often have smooth surfaces limiting cellular adhesion and interaction**.

AIM: To investigate the impact of femtosecond (fs) and CO_2 laser surface texturing on the roughness, microstructure, and dissolution behavior (including ion release and apatite formation) of 45S5 and ICIE16 BGs under varying laser parameters (power, speed, spacing), and, in this way, understand **how these modifications affect material properties to support innovations in implant technology**.

METHOD

Materials: 45S5 and ICIE16 BGs were prepared by **melting analytical grade reagents** (SiO_2, $CaCO_3$, $CaHPO_4 \cdot 2H_2O$, Na_2CO_3, K_2CO_3) **in a Pt crucible, casting into graphite molds, and annealing at 520ºC.**

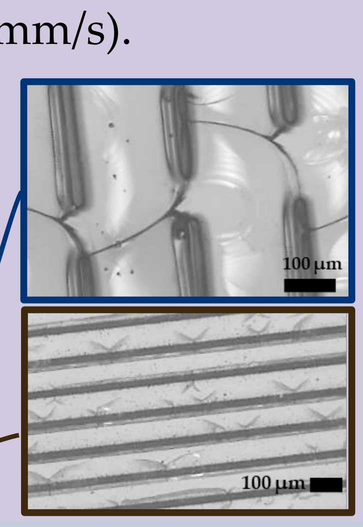
Oxide	Composition (wt%) ICIE16	45S5
SiO_2	48.0	45
CaO	32.9	24.5
P_2O_5	2.5	6.0
K_2O	10.0	-
Na_2O	6.6	24.5
NC	2.04	1.90



Laser Surface Texturing:

- **Ytterbium fs laser** (532 nm wavelength, 25W power, 20,000 Hz repetition rate) created linear grooves/grids.
- **Rofin Coherent CO_2 Laser** (10,600 nm wavelength, 25W Synrad source) created patterns with varying power (6-25W) and scanning speed (40-500 mm/s).

Parameters (Units)	Laser Source CO_2	fs Yb
Wavelength (nm)	10,600	532
Power (W)	6–25	25
Scanning speed (mm/s)	40–500	100
Lattice spacing (μm)	30–500	100 and 300
Number of Passes	1.0	1–50



Optical micrographs of the textured pattern obtained by CO_2 and fs LSM of 45S5.

Surface Characterization:

- **Optical interferometric profilometry** measured **roughness**. And for **morphology** were used, Nikon SMZ1000 **stereomicroscope** and JEOL JSM-6510 **SEM**.
- **Analyzed structure** with **Raman** spectroscopy (LAbRam-HR800, 488 nm Ar laser).
- **Contact angle** measured using the **sessile drop technique** with bi-distilled water.
- **Vickers hardness** (Shimadzu tester) and **fracture toughness** (K_{Ic}) measured near the modified surfaces and from radial cracks post-indentation.

Dissolution Test of samples immersed in **0.05 M Tris-HCl buffer** (pH 7.4, 36.5ºC) for up to **75 days. Surface changes** (morphology, roughness, apatite formation) **monitored using microscopy and OIP at intervals**. Finally, an evaluation of **ion release** (ICP) and HAP layer formation (SEM) was a key part of this in vitro behavior evaluation.

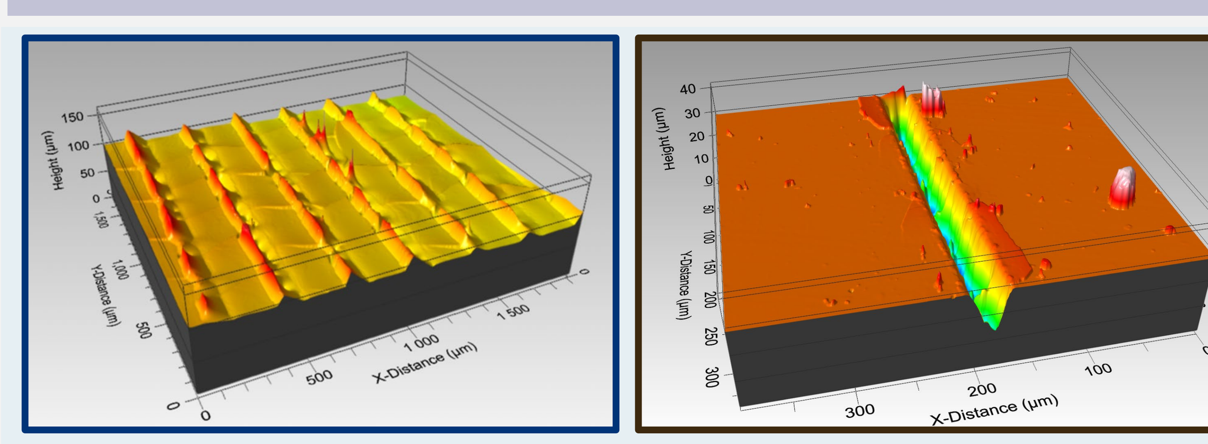
RESULTS & DISCUSSION

CO_2 LSM: Induced **significant roughness (Sq up to 10μm) creating well-defined remelted zones** with some cracking due to thermoelastic effects. Hardness was comparable to reference but more variable; **contact angle increased**. **Sq ≈20μm after 75 days in Tris-HCl**, maintaining apatite precipitation ability. This indicates potential for **long-term osteoconductivity enhancement**, promoting **faster HAP layer formation.**

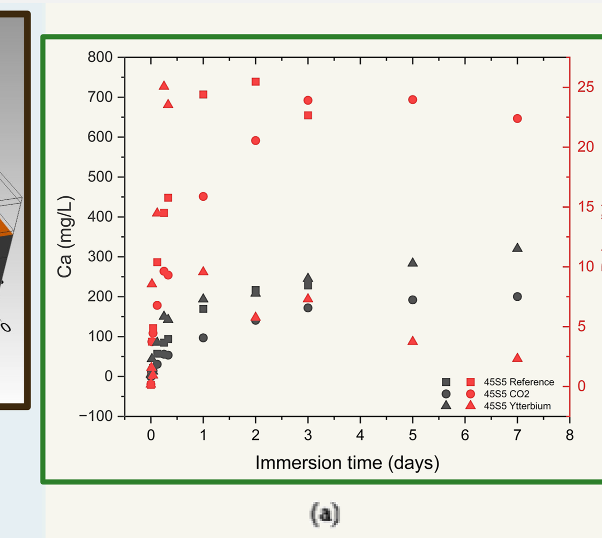
Yt fs LSM: V-shaped grooves via ablation with **minimal remelted material**; roughness increased with number of passes. **Reduced hardness** compared to reference BGs; contact angle not significantly changed.

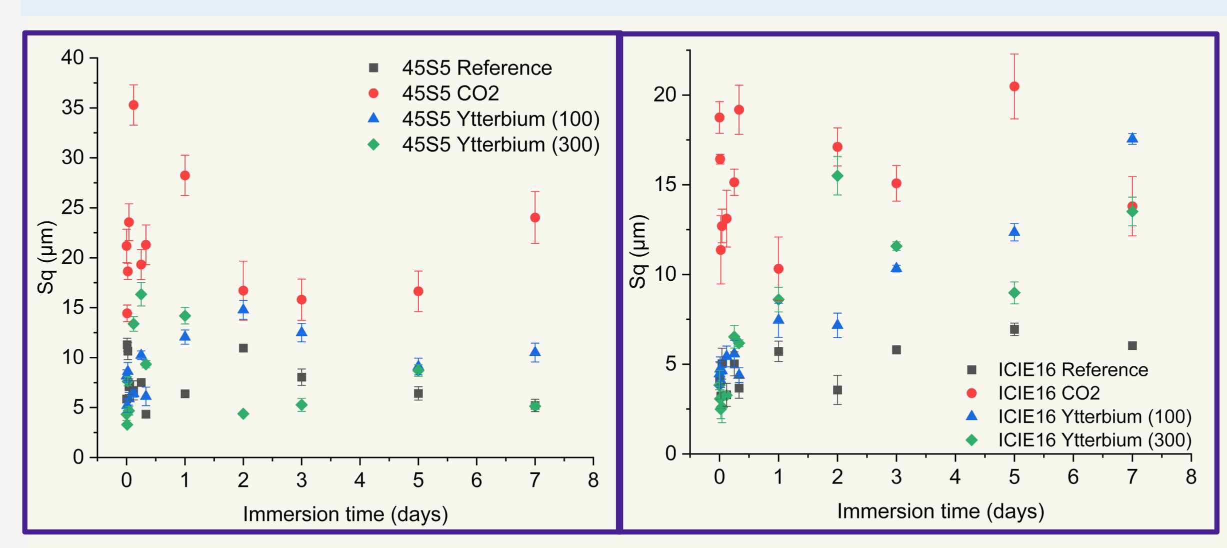
Preferential apatite precipitation ability within grooves, on 45S5 the pattern **lost long-term as apatite filled**; effective for **short-term effects**. However, **on ICIE16, this precipitation was maintained long-term,** with apatite coating forming.

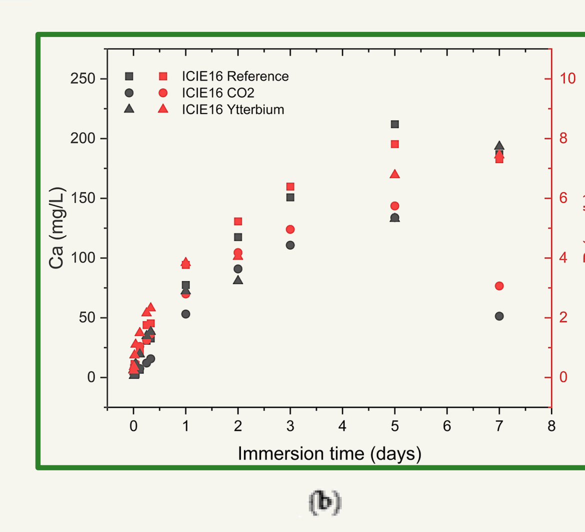
CO_2 LSM on 45S5 showed a high release of ions, instead **ICIE16 showed an initial passivation layer**, indicating a **more controlled dissolution and better maintenance of its texture initially**, while still allowing for HAP formation. In contrast the **fs LSM on ICIE16 led to preferential apatite formation in the grooves**, suggesting tailored ion release or surface chemistry within these features.



3D maps of the textured pattern obtained by CO_2 and fs LSM of 45S5: **(a) pattern spacing 300 μm; (b) 100 μm.**







Sq (L) and **ICP (R)** graphs for the specimens subjected to immersion: (**a**) 45S5; (**b**) ICIE16.

CONCLUSION

- **CO_2 →** Increasing contact angle and roughness, **maintained long-term in Tris, enhancing potential for cellular response while preserving apatite precipitation**.
- **fs → Precise V-shaped grooves** via ablation **lost long-term** on **45S5**, and which provide **sustained**, **long-term preferential apatite precipitation** on **ICIE16**, showing potential for space-resolved osteoconductivity.

The choice of laser and BG composition dictates short- and long-term surface characteristics.

FUTURE WORK / REFERENCES

Further studies will assess **osteoblastic cell interaction with modified surfaces** and potential enhancement of bone osseointegration. Also, it will be interesting to **investigate the impact on angiogenesis** and to **explore other stable BGs** (e.g., 13-93).

Key References: [1] Gill, T.K.; et al. Lancet Rheumatol. 2023, 5, e670–e682. [2] Hench, L.L. J. Am. Ceram. Soc. 1991, 74, 1487–1510. [3] Sharma, K.; et al. J. Non Cryst. Solids 2016, 440, 43–48. [4] Shaikh, S.; et al. J. Laser Appl. 2017, 29, 022004. [5] Comesaña, R.; et al. Acta Biomater. 2011, 7, 3476–3487.