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RSE Ricerca Sistema Energetico

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SOLID PARTICLE EROSION OF STANDARD AND ADVANCED THERMAL BARRIER COATINGS

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Ackowledgements

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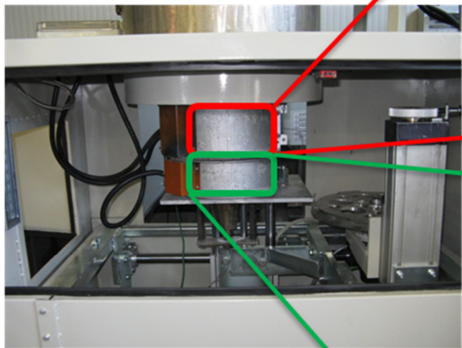
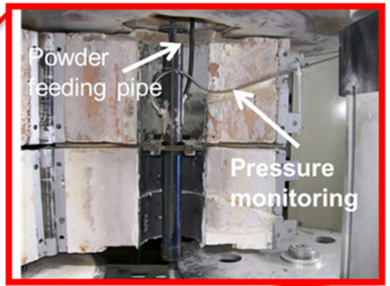
TOwards design and Processing of advanced, comPetitive thermal barrier COATing systems - TOPPCOAT, STREP 6 project no. AST4-CT-2005-516 149, Project report, 2010.

This work is funded through the European Metrology Research Programme (EMRP) Project IND61 Metrology to Enable High Temperature Erosion Testing (METROSION). The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

RSE SPE Jet Tester

Main furnace with the coil for air inside



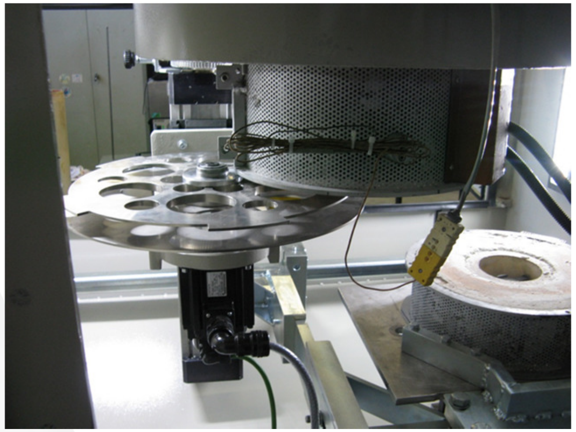


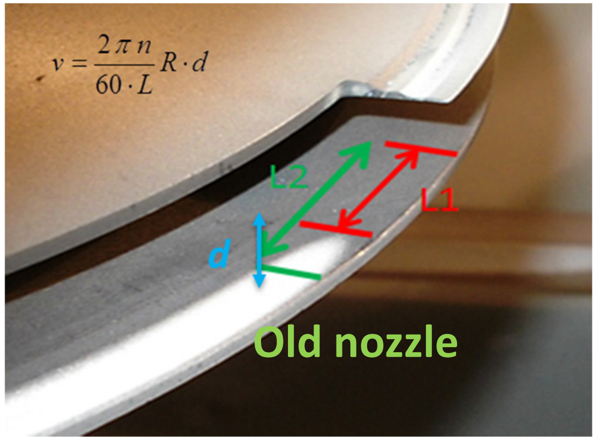
- Impact angles 30°, 45°, 60° and 90°
- Temperature RT to 950°C.
- Velocity up to 250m/s.

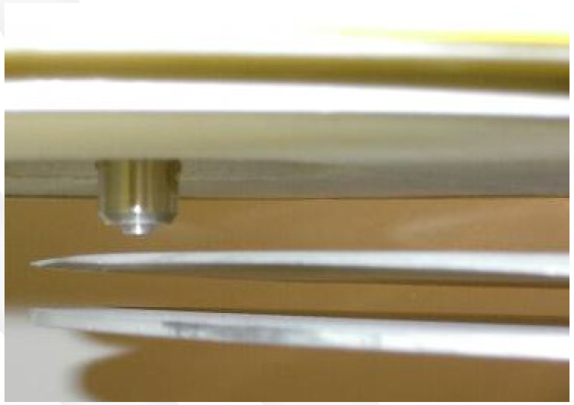
In agreement with the ASTM G211-2014 Standard

Standard Test Method for Conducting Elevated Temperature Erosion Tests by Solid Particle Impingement Using Gas Jets

The RSE Jet tester - Speed measurement

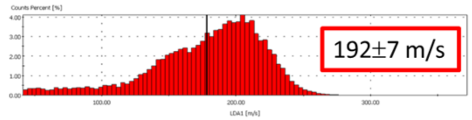




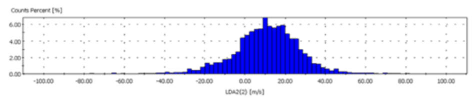


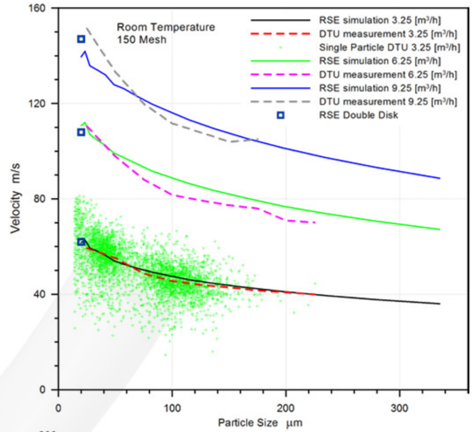
Five windows uniformly distributed along the upper disk to increase the statistics

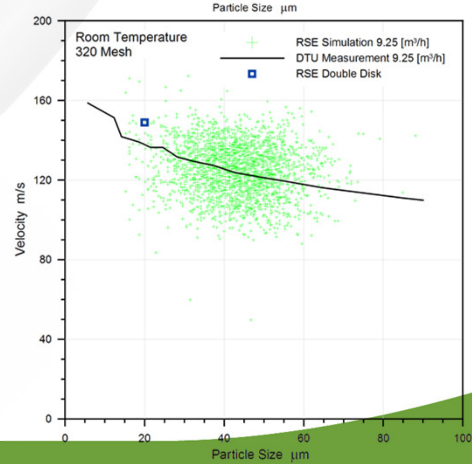
Laser Doppler Velocimetry



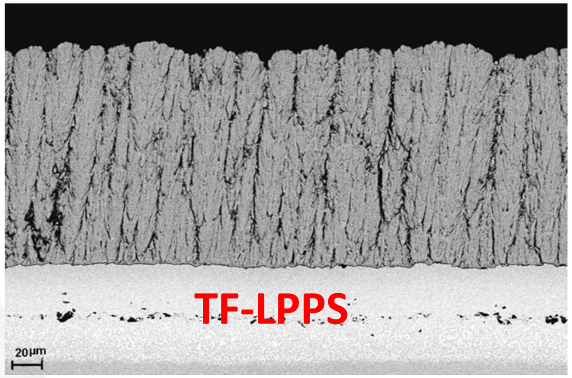
Velocity Histogram at Center of Jet

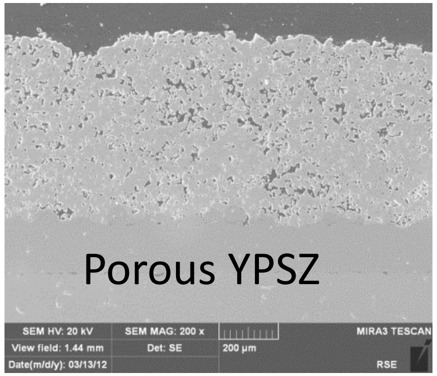


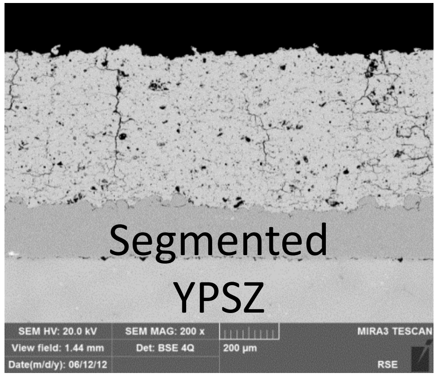


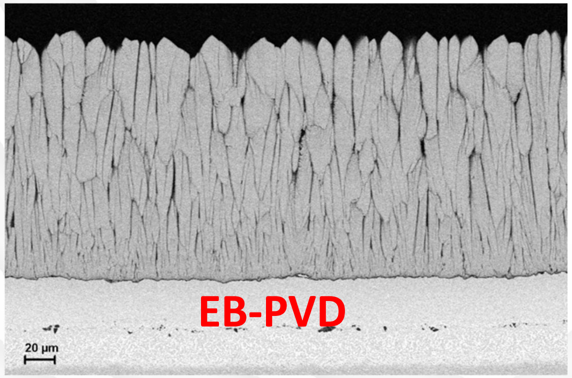


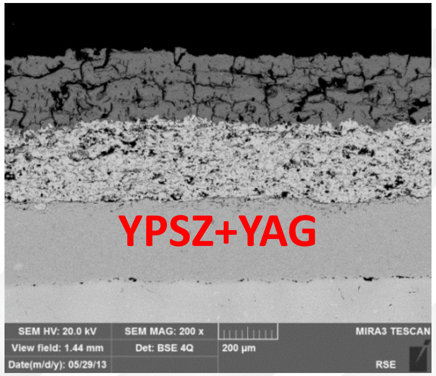
Sample morphology and chemical composition

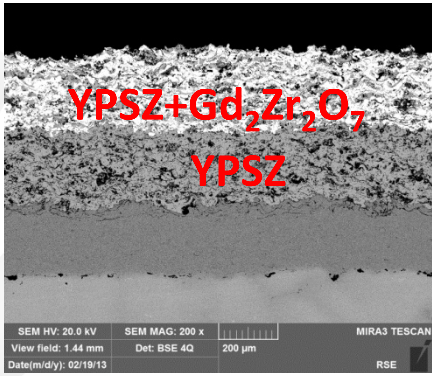




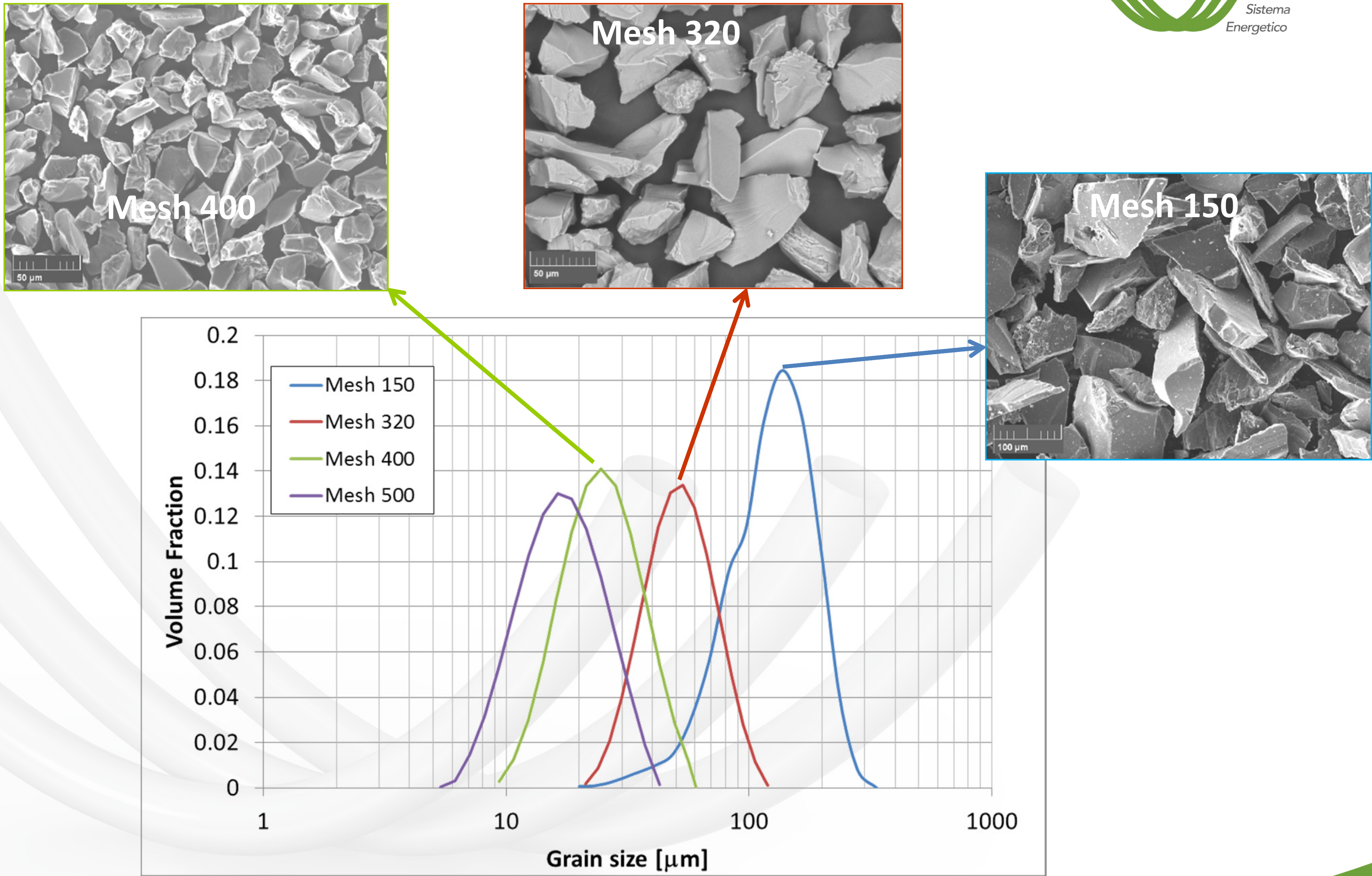




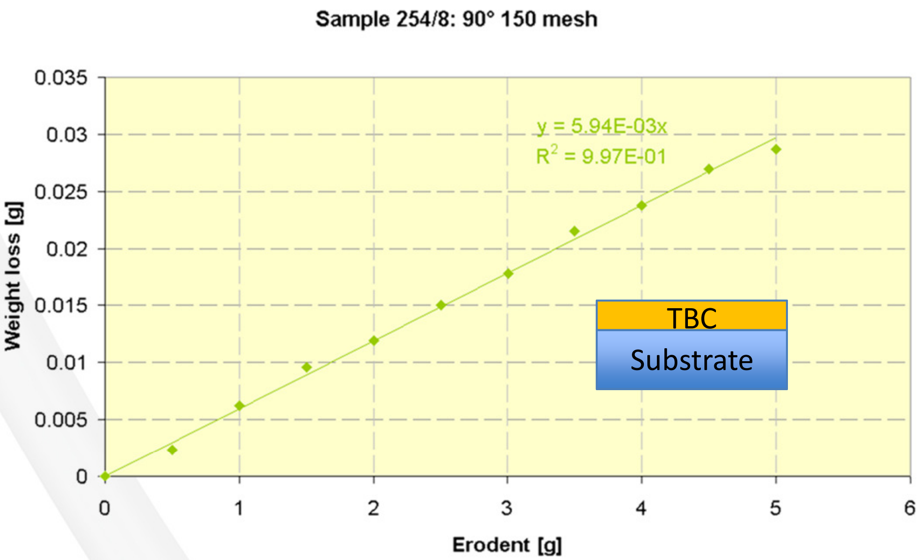


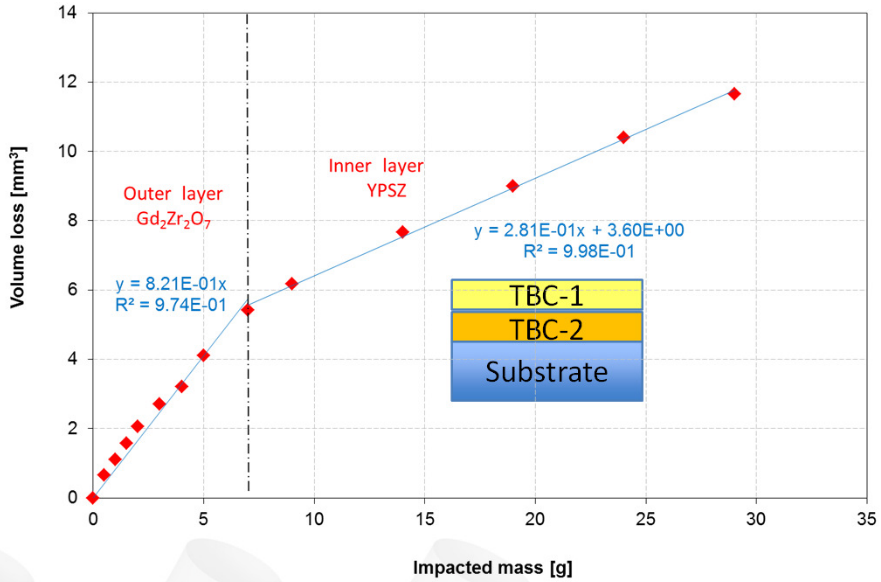


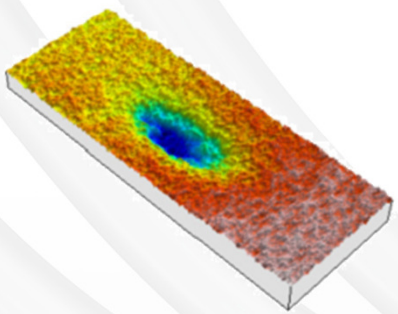
Erodent morphology

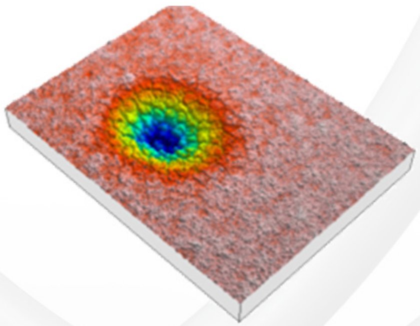


Experimental procedure



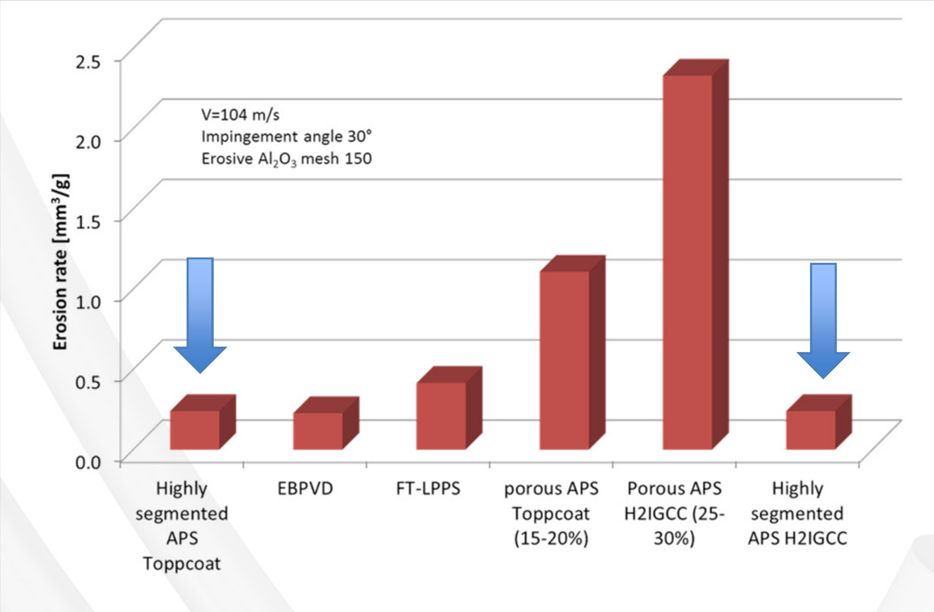


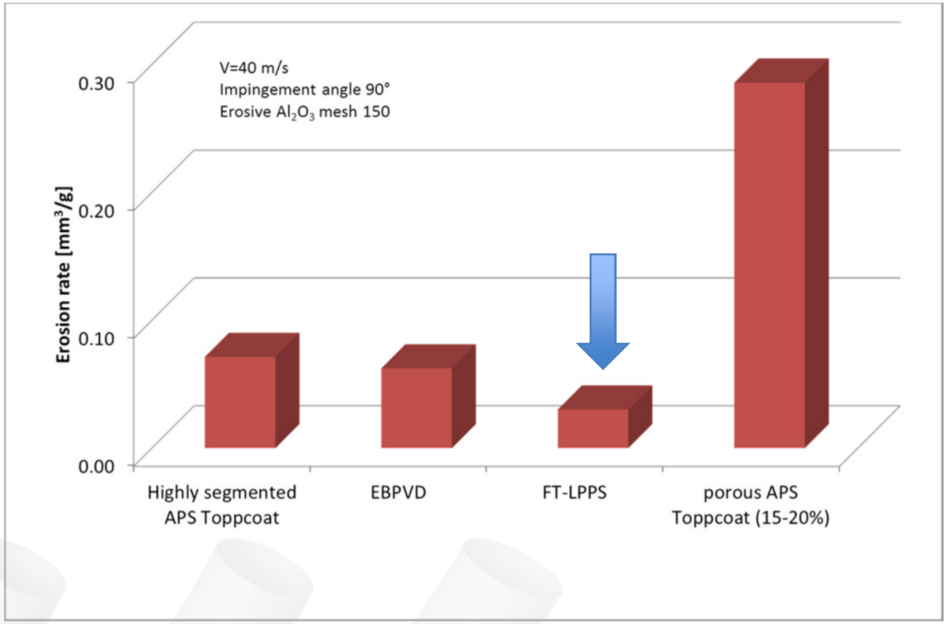




Weight or volume (when density is known) loss evaluation by weighting samples, but surface mapping could be performed as well.

Effect of TBC microstructure -1





•Highly segmented APS TBC and TF-LPPS perform similarly to columnar structured EB-PVD TBCs, credited as the best erosion resistant TBCs, because of the low porosity content and the columnar structure able to better withstand the impact of high energy erodent particles.

•The porosity content in porous APS significantly affects the erosion resistance: the higher the porosity content the lower the hardness and the toughness of the TBC and thus the lower the erosion resistance of very porous TBCs.

Effect of TBC microstructure -2

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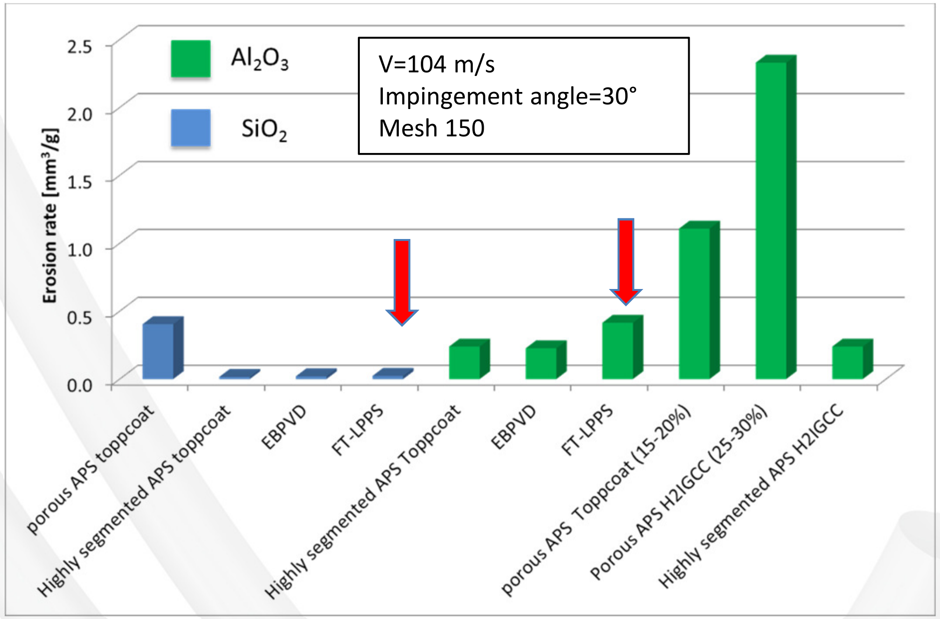
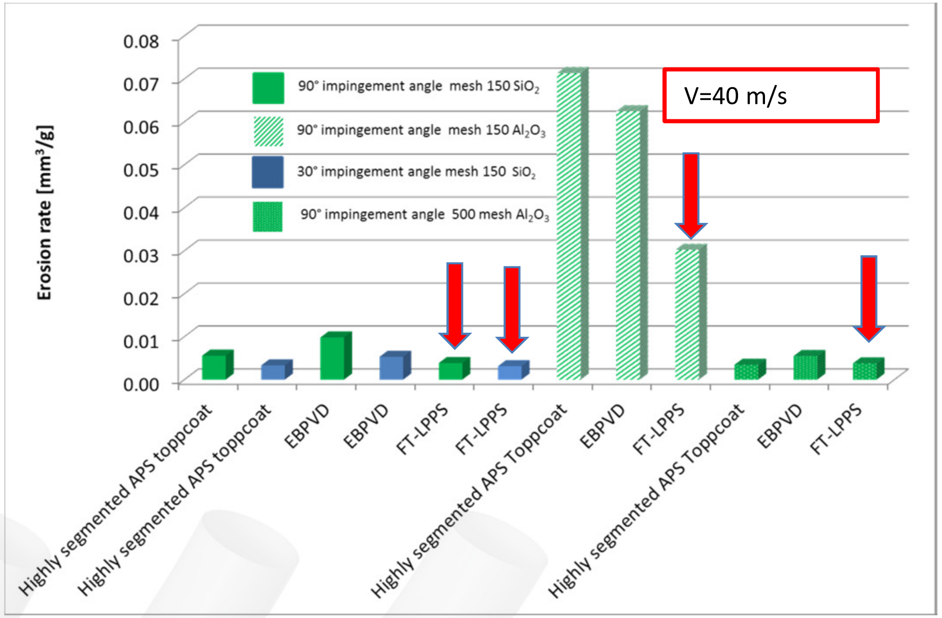


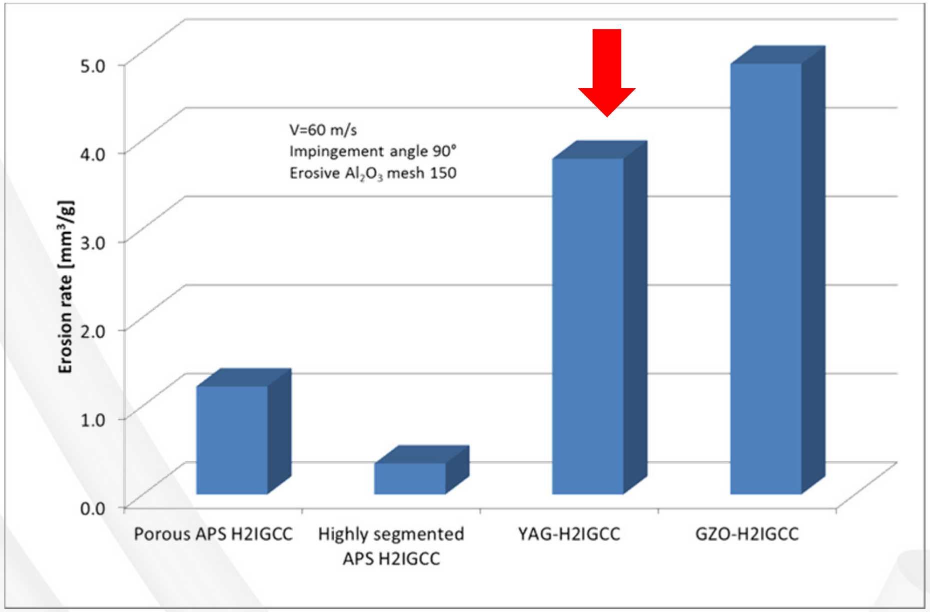


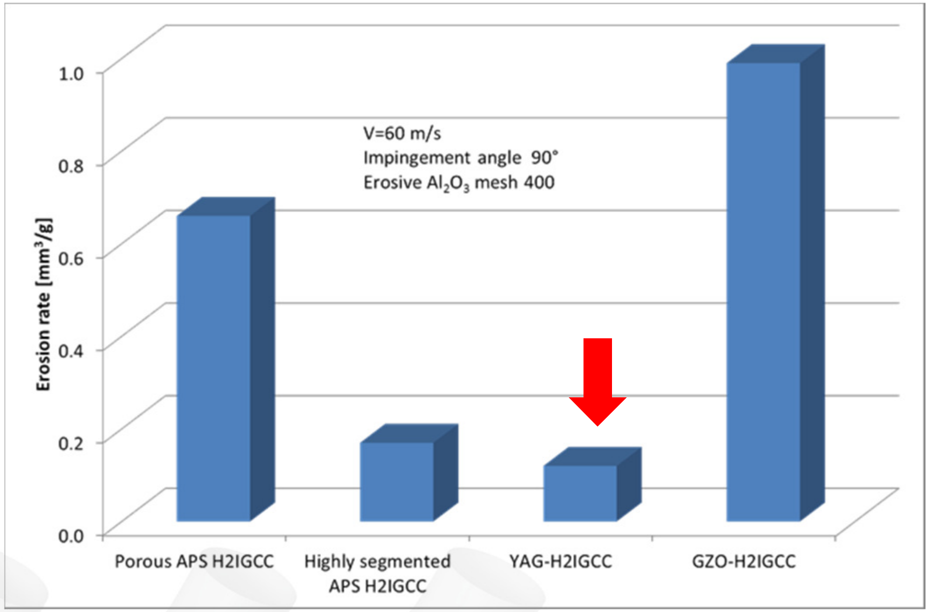
•TF-LPPS is the best performer when erodent particles have low energy; this provides indications that failure mode changes in TF-LPPS TBC as a function of energy and that this change take place between the worst and the others testing conditions.

•A general behavior can be observed as a function the erodent features:

- Alumina powder is a more effective erodent (**one order of magnitude**) compared to microquartz owing to the higher hardness and density of alumina.

Effect of TBC microstructure/erodent

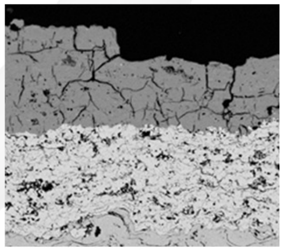


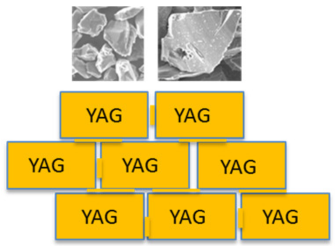


The YPSZ-YAG TBC performs better or comparably to highly segmented TBC, when fine powder is used; on the contrary, for coarse erodent YAG TBC shows a poor erosion resistance.

YAG toughness is 1/5 of that of YPSZ (i.e. <2 MPa $m^{1/2}$ vs. 10 MPa $m^{1/2}$) but the very dense structure of these bricks, together with the intrinsic hardness higher (16.5 – 17 GPa) than that of YPSZ (13 GPa), could justify the very good erosion resistance.

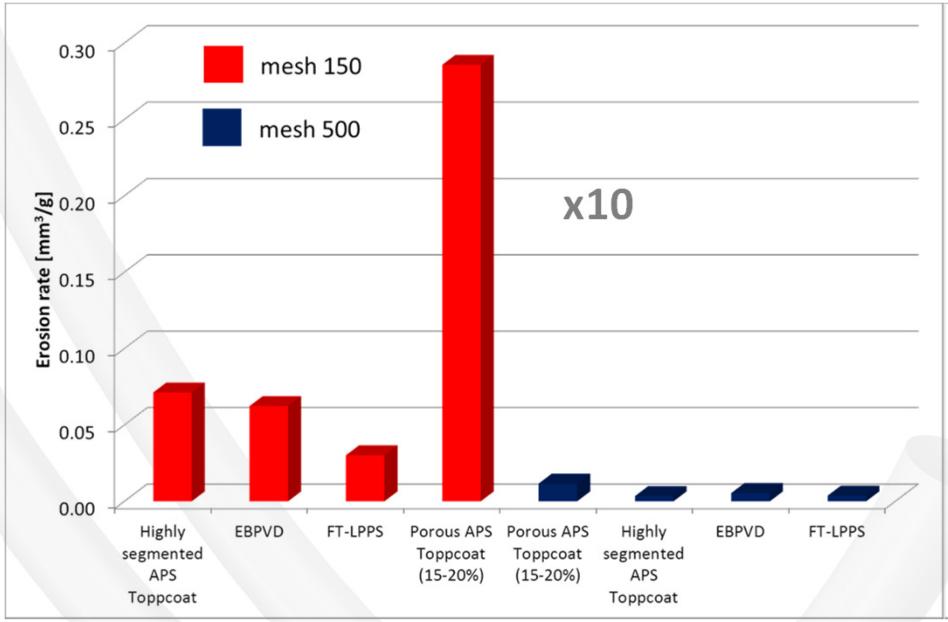
GZO presents a very poor resistance to erosion, compared to other TBCs in all testing conditions.



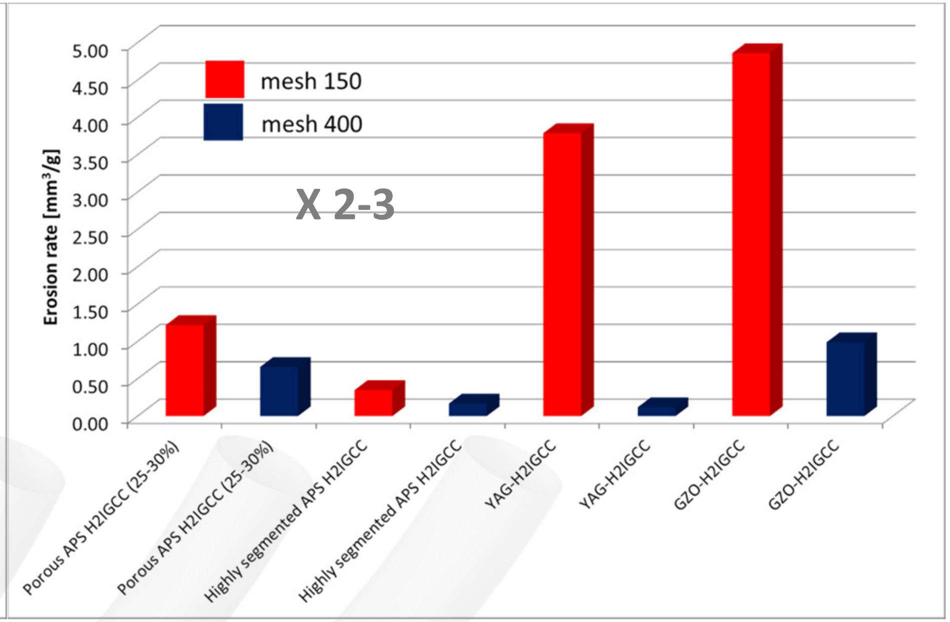


Erodent size effect

V=40 m/s 90°

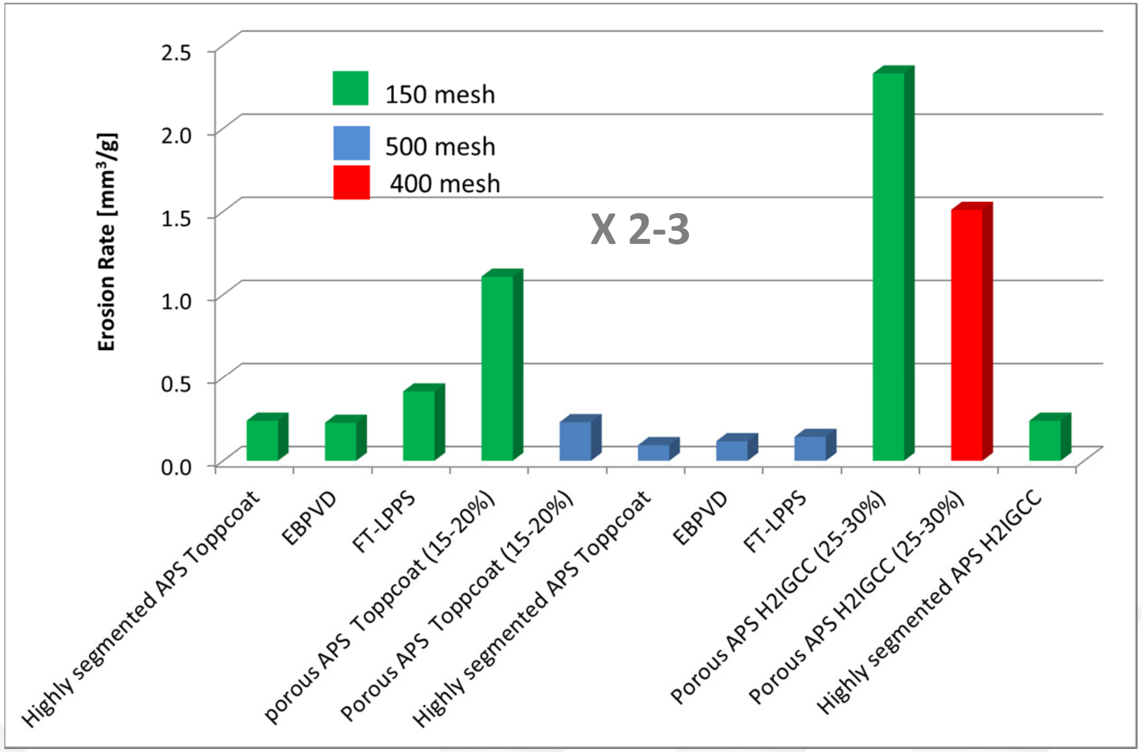


V=60 m/s 90°



Erodent size effect

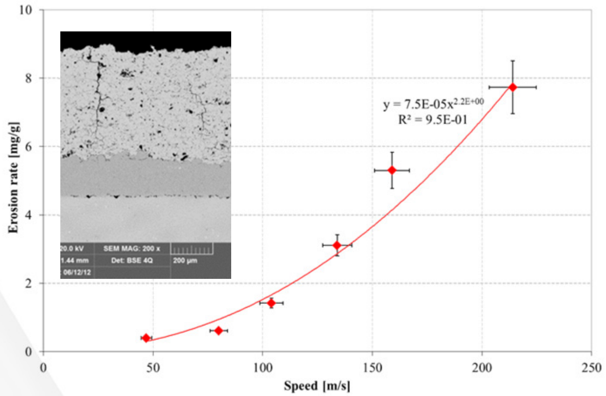
V=104 m/s 30°



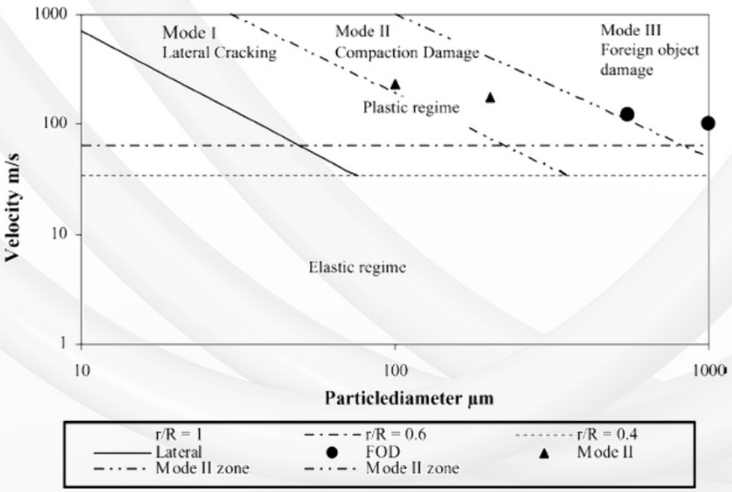
The coarser the erosive powder the higher the erosion rate for all the TBCs samples.
Since tests have been carried out setting up the same impingement speed, **the energy of the single particle** is essential in determining the **damage mechanism** and erosion severity occurring in the TBC. **It is conceivable that an energy threshold for single impact damage exists and this is strictly correlated to the microstructure of the TBC**

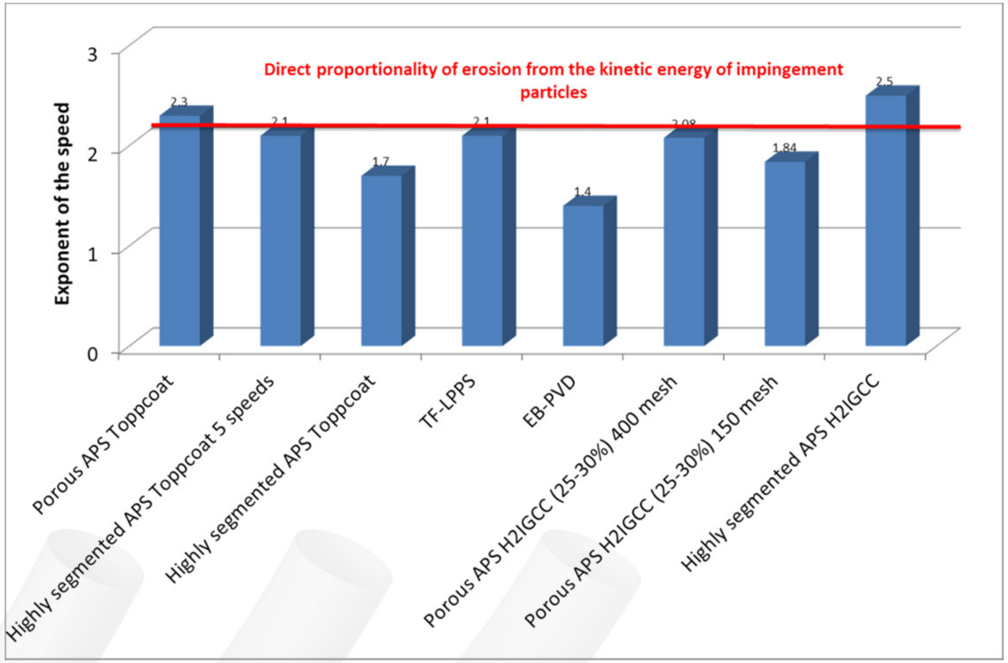
The impingement speed effect

$$w_e \propto v^n$$



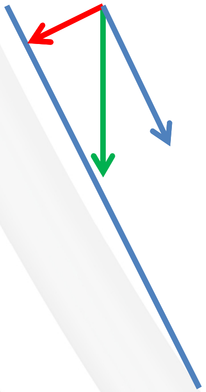
R.G. Wellman et al. / Wear 258 (2005) 349–356

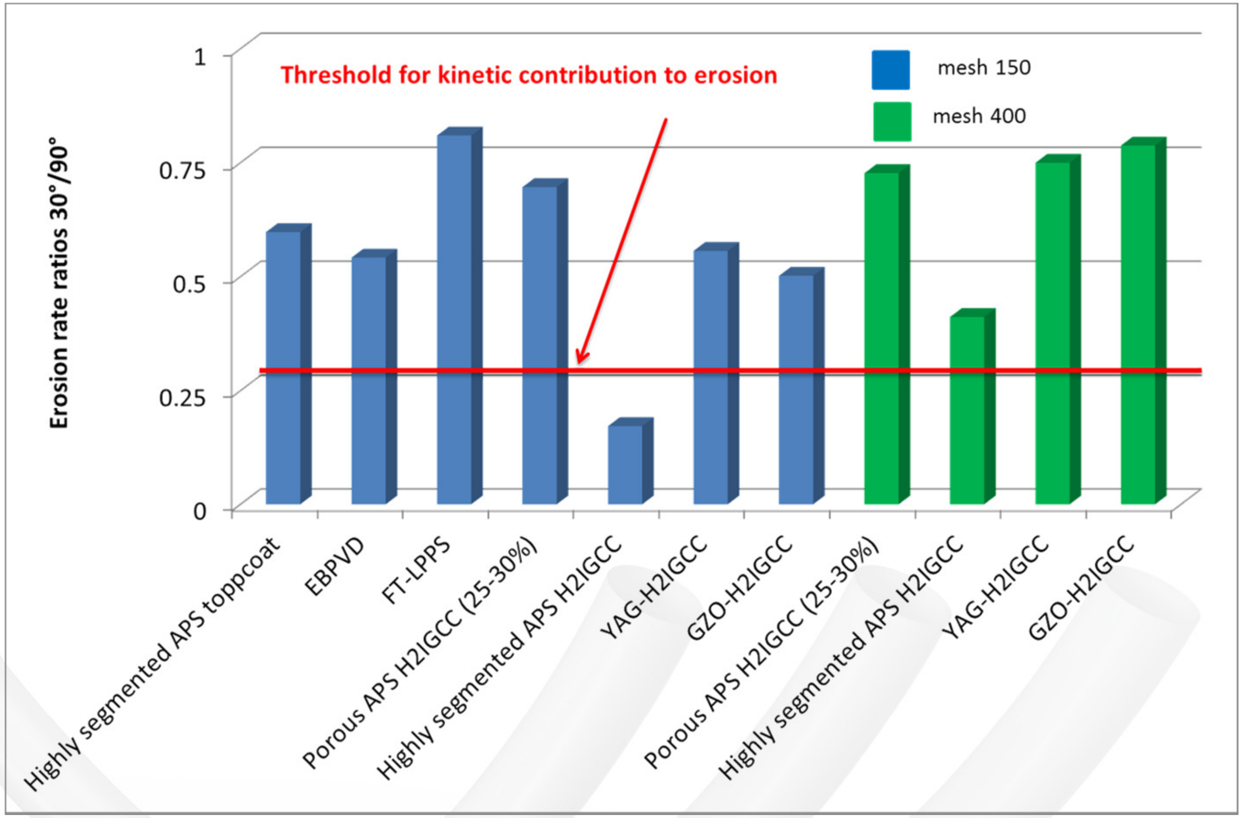




There is evidence of a direct proportionality between the erosion rate and the kinetic energy (i.e. *n*=2). Only EB-PVD samples exhibit a significantly lower value of *n*, as also reported in the literature (*n*=1) (J.R. Nicholls et al Wear 233-235 (1999))

Effect of the impingement angle

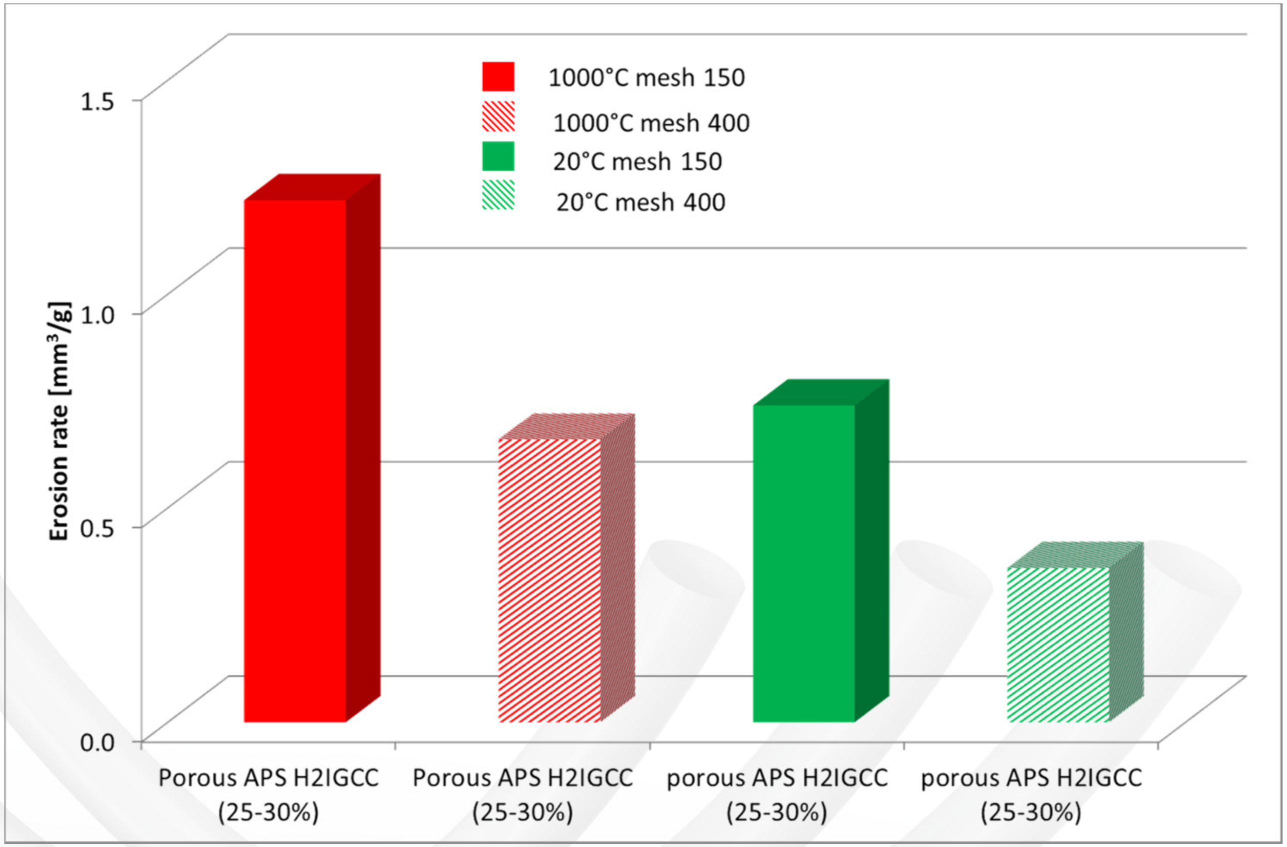




Erosion rate decreases with the impingement angle from 90° to 30° but the reduction is smaller than that estimated by considering the contribution to erosion of the speed component perpendicular to the sample surface $w_e = (v sin\varphi)^2$. Similar decreases are also reported in the literature.

TBC plastic deformations for glazing angles impacts have to be included to explain these outcomes

Effect of sample testing temperature



Erosion rate at high temperature is twice that at RT when warm erodent particles are used

Failure mechanisms of the TBCs

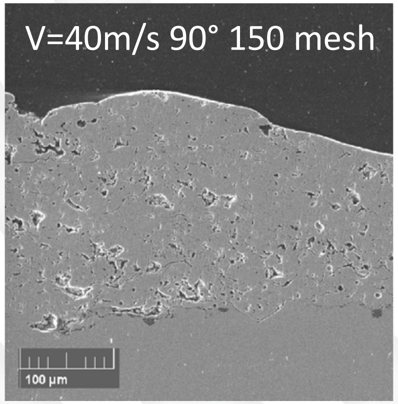
APS

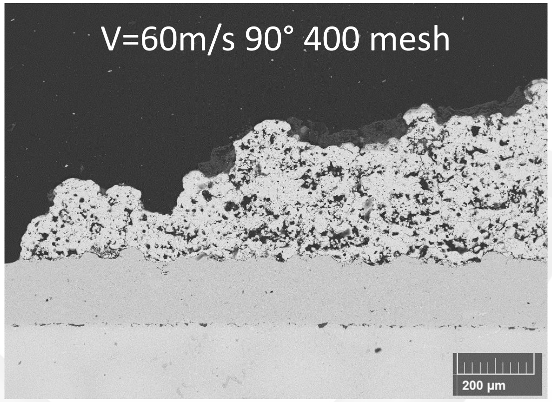
Mode I: **surface indentation** by erodent particles (plowing of local furrows): low erosion rate

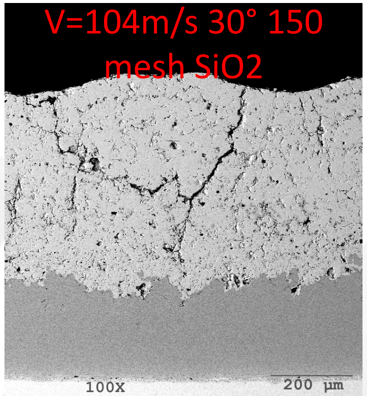
Mode II: **crack nucleation** in the impact area and propagation through and around individual splats: moderate erosion rate

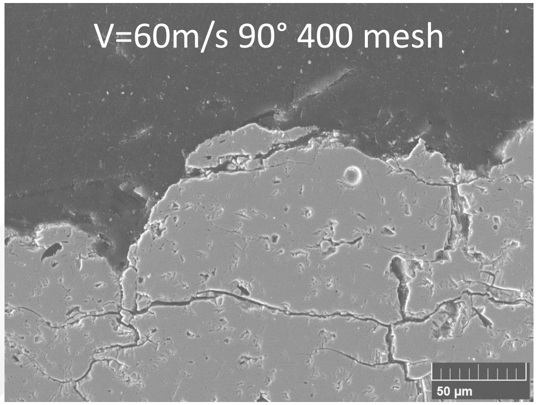
Mode III: **crack propagation** through pores and cracks typical of the APS microstructure promoting erosion of clusters of splats (tunneling): high erosion rates

H.E. Eaton, R.C. Novak Surf. Coat technol. 30, (1987) 41- 50









Densification of a thin layer of APS TBCs is observed

Far from the maximum erosion footprint alumina particles stick on the TBC surface

Mode II and III typically occur in APS TBCs in the testing conditions considered along with this study.

Densification of a thin layer of APS TBCs is observed

Mode II and III typically occur in APS TBCs in the testing conditions considered along with this study.

Failure mechanisms of the TBCs

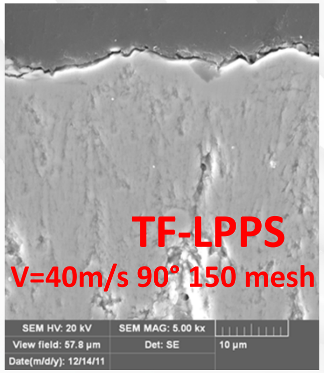
EB-PVD

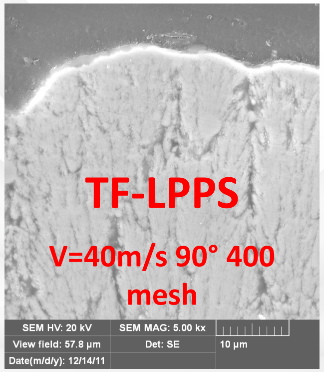
Mode I: low particle size/momentum. The response is elastic and zones of local tensile stress develop near the surface in columns adjacent to the impact site, caused by column bending as the projectile penetrates.

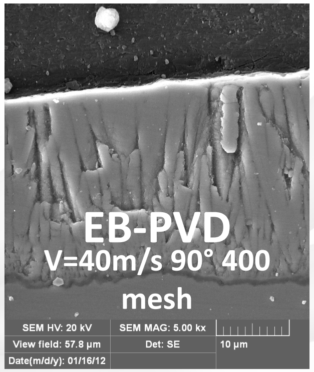
Mode II: At intermediate particle size and momentum, a shallow thin layer zone forms by multiple impacts. Subsequent impacts induce stress concentrations at the intersection of the dense and columnar regions, which cause portions of the dense layer to detach from the underlying columns.

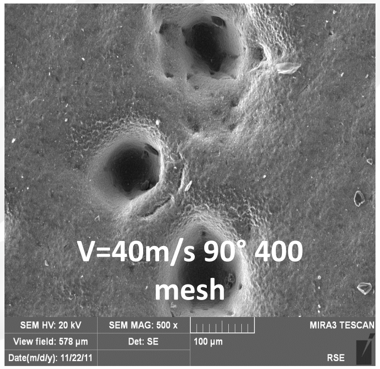
Mode III:When large particles impact with high momentum at high temperature, most of the kinetic energy is absorbed by plastic deformation and densification of the TBC. The deformation may be accompanied by kink bands around the perimeter of the plastic zone. When present, these bands intersect the TGO, and initiate delamination cracks that extend outward from the impact center, parallel to the interface.

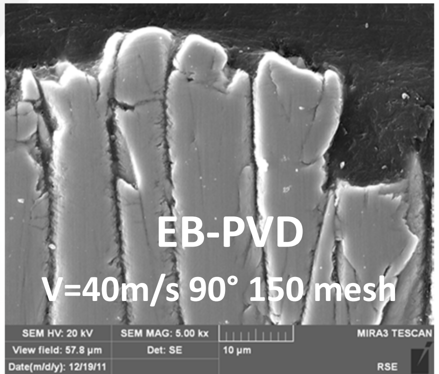
X. Chen et al, Wear 256 (2004) 735–746
N.A. Fleck, Th. Zisis Wear 268 (2010) 1214-1224





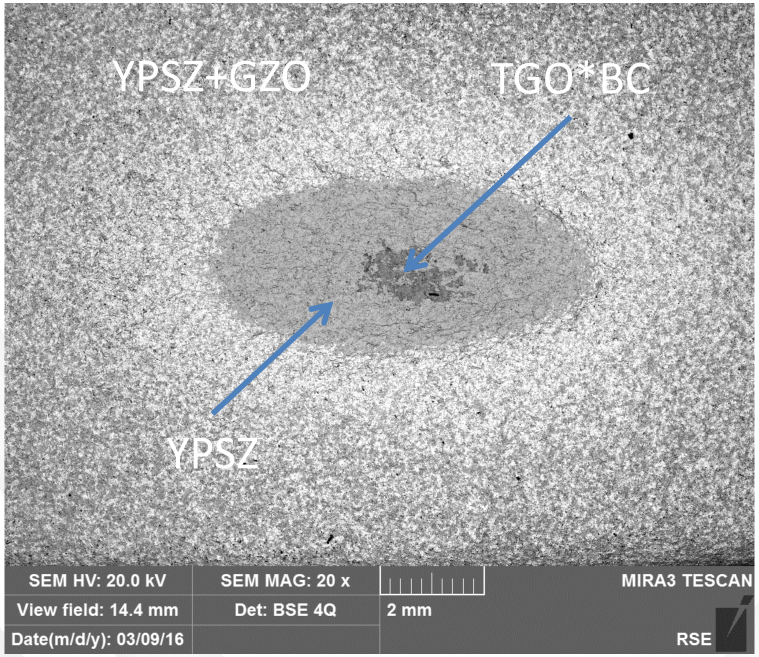


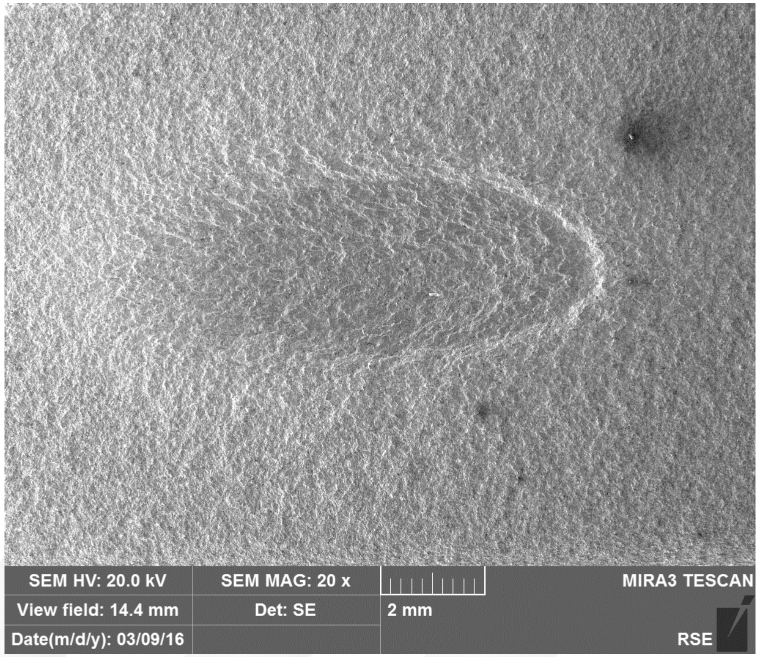




Densification layer increases from 0.5 to 3 µm increasing the grain size of Al_2O_3 from 500 mesh to 150 mesh

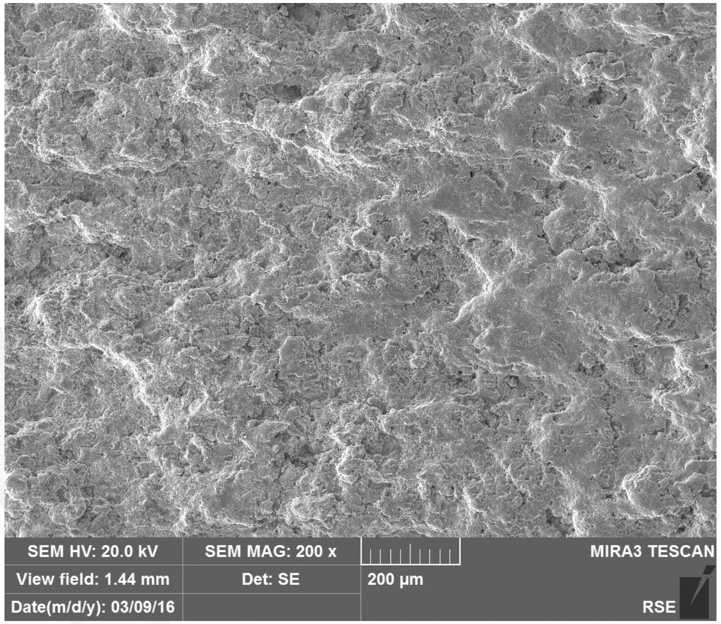
Failure mechanisms of the TBCs (fine powder)

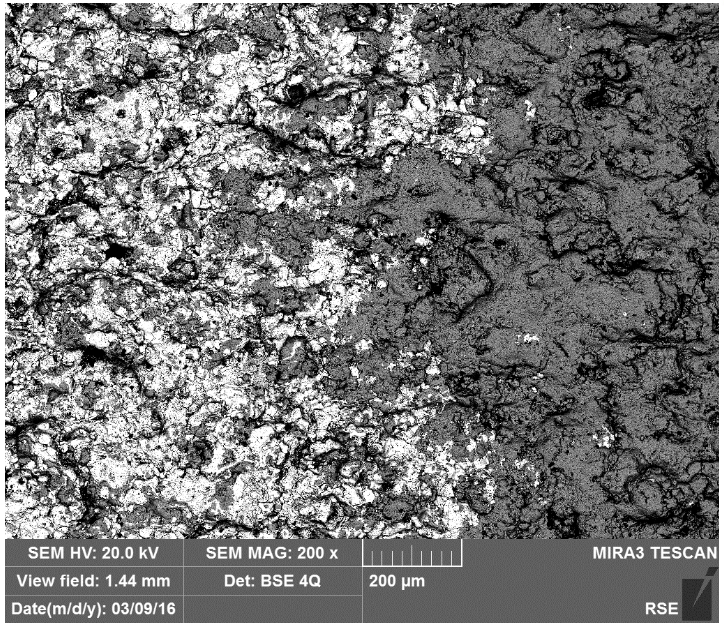


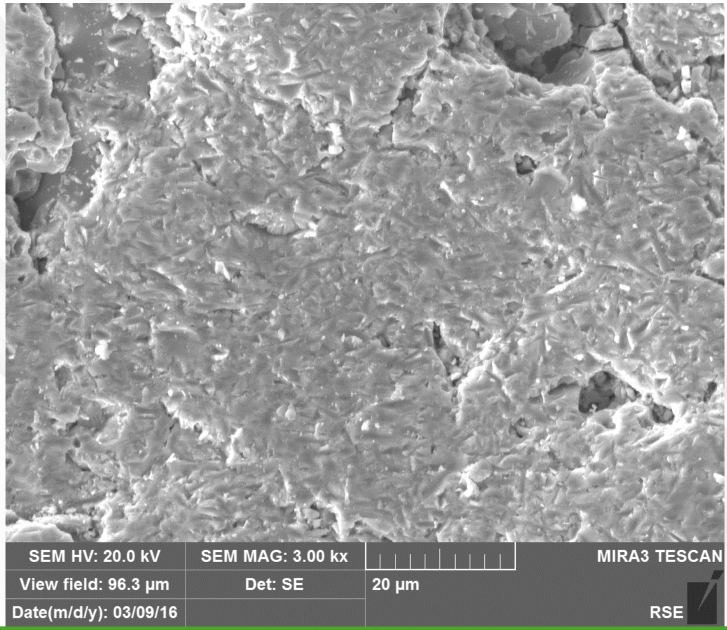


Erosion by layer by layer splats removal

Failure mechanisms of the TBCs (fine powder)

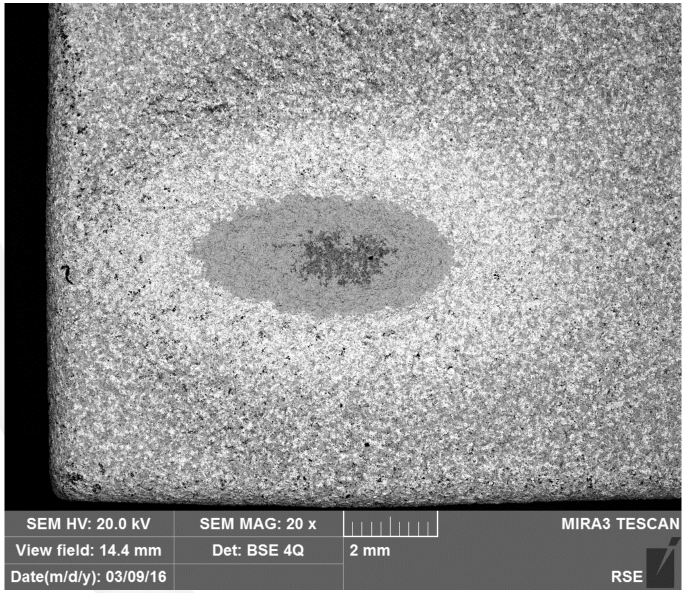


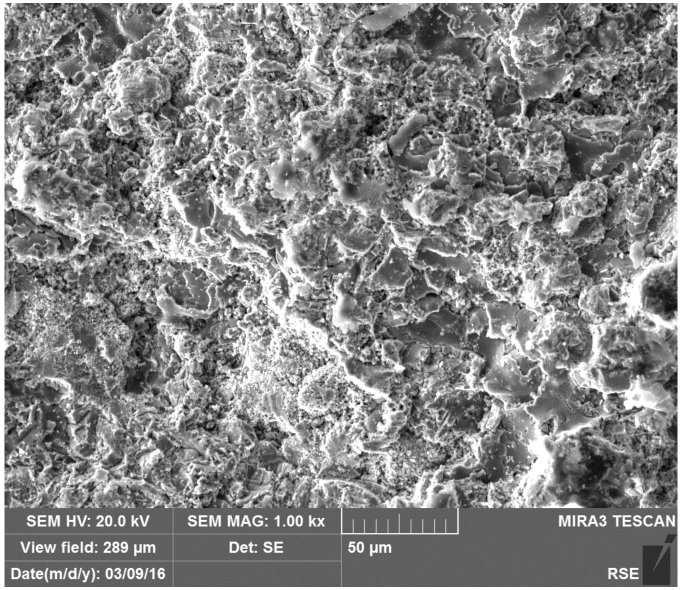




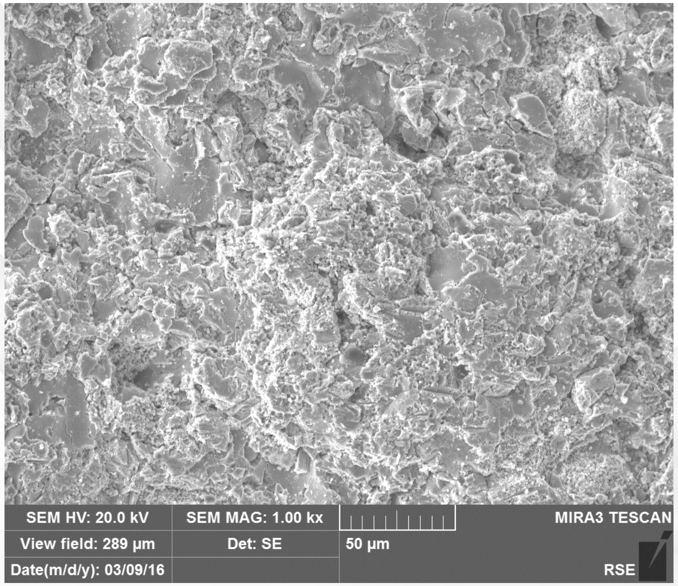
Scratches of single small erodent particles (mesh 400) can be clearly observed at high magnification. At High temperature TBC behaves as a ductile material.
Splats are smoothed by particle impingement.
Mode I

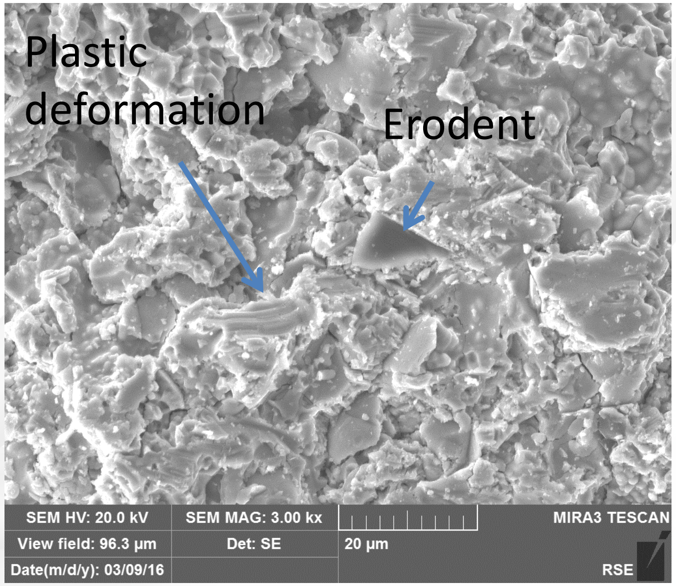
Failure mechanisms of the TBCs (coarse powder)





Crack propagation and fracture of TBC splats and cluster of splats seems to be the main damage mechanisms when coarse powder is used as erodent. Ductile behaviour of TBC can be still observed.
A significant embedding of erodent particle can be observed. **Mode II and III**





Conclusive remarks

- HS and TF-LPPS exhibit in general better erosion resistance (similar as EB-PVD) regardless of experimental conditions, whereas YAG coating, due to its peculiar brick-like structure, seems to be a very interesting advanced erosion resistant TBCs, at least when erosion particles mean diameter does not exceed about 25 µm.

- The porous, highly segmented and Gd-containing TBCs show the same erosion mechanisms proceeding through single or multiple splat removal through crack propagation along the boundaries.

- Test parameters affect the measured erosion rate (erodent size, hardness, and density. Impingement angle, speed and temperature)

- Single particle kinetic energy controls the damage mode for both EBPVD and PS TBCs

- Failure mechanism for columnar EB-PVD and TF-LPPS is mainly mode II (densification and cracking)

Conclusive remarks

- At shallow angles also the velocity component parallel to the surface contributes to the damage mechanisms, owing to plastic deformations taking place in the TBC especially at high temperature.
- Increasing testing temperature (from RT to 1000°C) as well as the grain size of erodent (400mesh to 150 mesh) the erosion rate increses by a factor of 2 or more
- Erosion rate depends on the square of the impingement speed for all the tested TBC

Thank you very much for your attention!