Development of advanced claddings for suppressing the hydrogen emission in the accident condition

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OECD/NEA Workshop on Accident Tolerant Fuels of LWRs
NEA Headquarters, Paris, 10-12 Dec. 2012

Accident-tolerant fuel claddings (ATFC)

- The development of accident-tolerant fuels is being considered as the breakthrough to the challenge facing nuclear fuels of LWRs after Fukushima Dai-ichi accident.

- New requirements have been emerged on the performance of fuel to provide a more extended safety margin.

- One of the goals to be reached with the accident-tolerant fuels is to reduce the hydrogen emission in the accident condition by improving the high temperature oxidation resistance of the claddings.

Fukushima accident

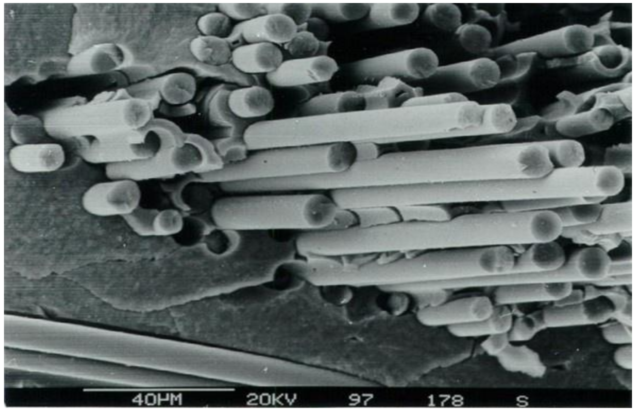
Hydrogen explosion

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$$

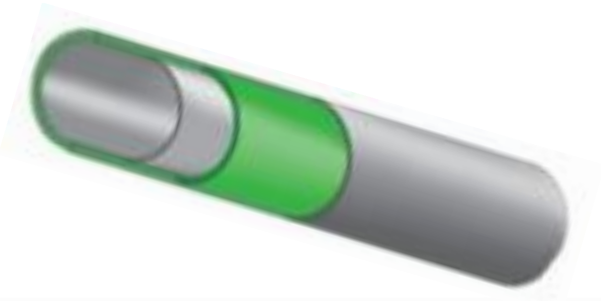
Challenges to ATFC

- Application of new materials raises many issues on the performance and the integrity of the claddings.

  - Oxidation resistance
  - Phase stability up to high temp.
  - Adhesion to the matrix
  - Thermal expansion coefficient
  - Neutron economy
  - Thermal conductivity
  - Irradiation susceptibility
  - Tube fabricability



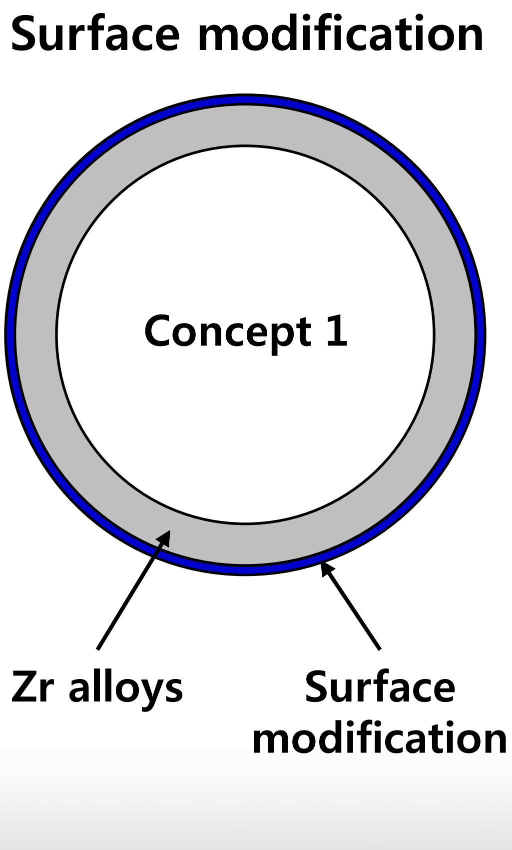
SiC_f/SiC composite

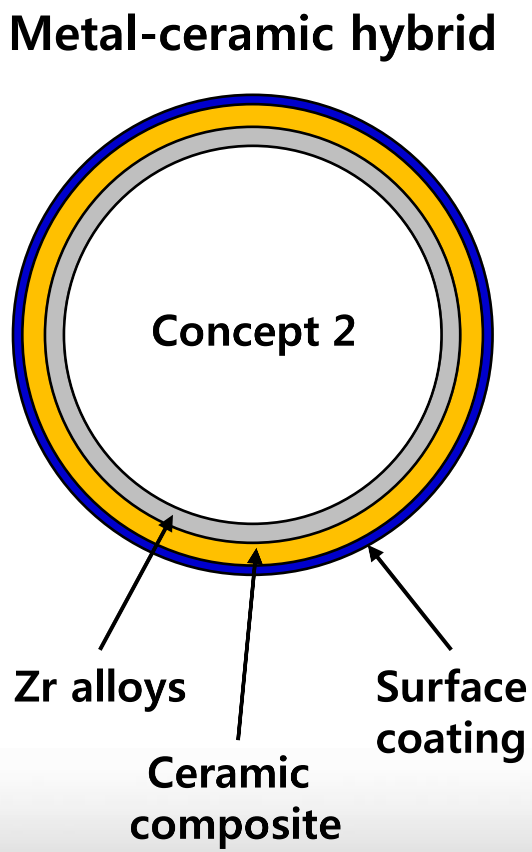


Zr-Mo-Zr cladding

Hydrogen-suppressed claddings

- KAERI launched the project to develop the accident tolerant fuel claddings with two major concepts.



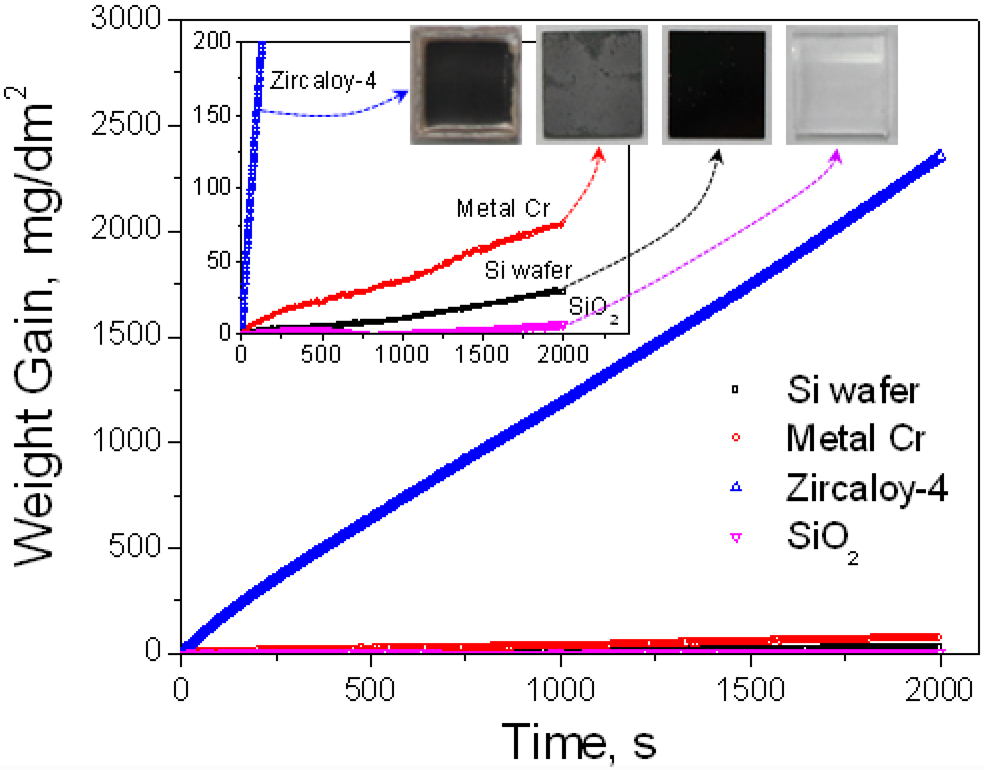


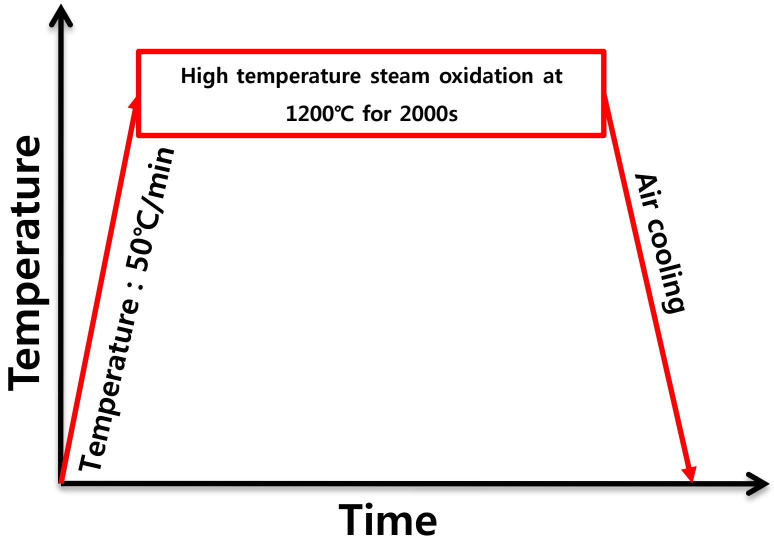
Candidate materials for surface modification

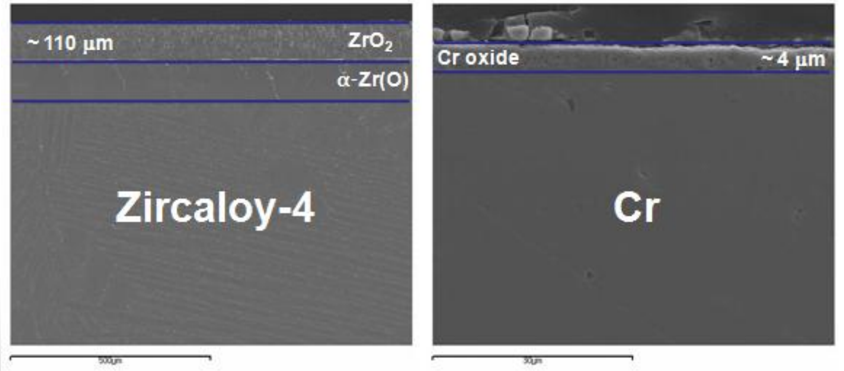
Materials for surface modification		Melting point (°C)	Thermal expansion coff. ($\times 10^{-6}$K)	Thermal conductivity (W/mK)	Neutron capture cross section (barn)
Oxide	Y_2O_3	2690	8.1	1.0	1.28(Y) 0.0002(O)
	SiO_2	1600	12.3	1.3	0.177(Si) 0.0002(O)
	Cr_2O_3	2400	9.0	2-5(coating)	3.05(Cr) 0.0002(O)
	Al_2O_3	2072	8.4	5-25(bulk)	0.231(Al) 0.0002(O)
	ZrO_2	2130	10.1	1.8-3.0	0.182(Zr) 0.0002(O)
Carbide	SiC	2545	<5	330	0.177(Si) 0.0035(C)
	Cr_3C_2	1895	10.3	13	3.05(Cr) 0.0035(C)
Nitride	ZrN	1960	7.24	10	0.185(Zr) 1.9(N)
Intermetallic compound	Al_3Ti	1350	13	205(Al) 21.9(Ti)	0.231(Al) 6.09(Ti)
Metal	Cr	1907	4.9	93.9	3.05(Cr)
	Si	1414	2.6	149	0.177(Si)
Substrate	Zr	1850	7.2	10	0.185(Zr)

High temperature oxidation behavior

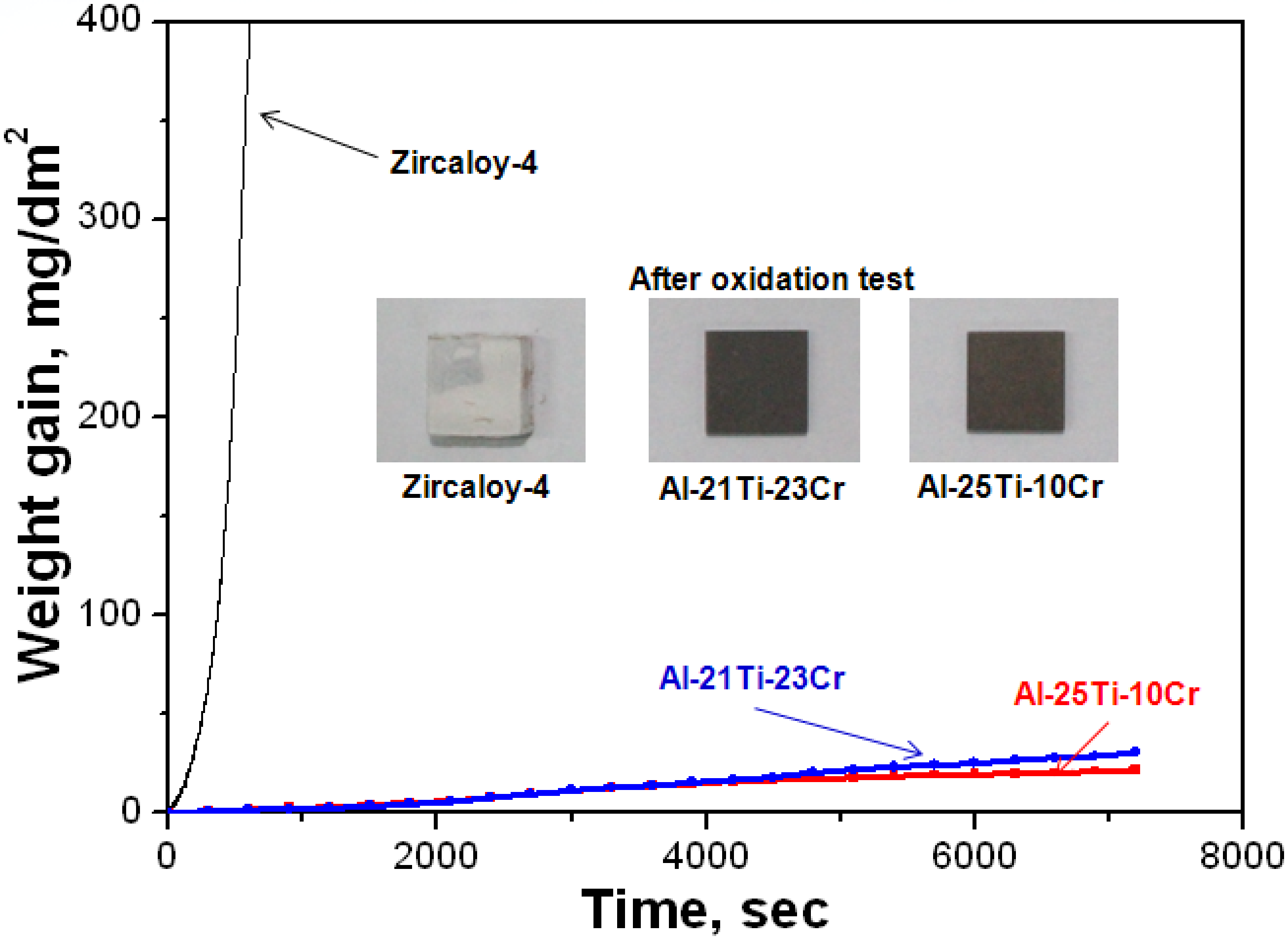
- High temperature steam oxidation resistance of the candidate materials was much higher than that of Zircaloy-4.





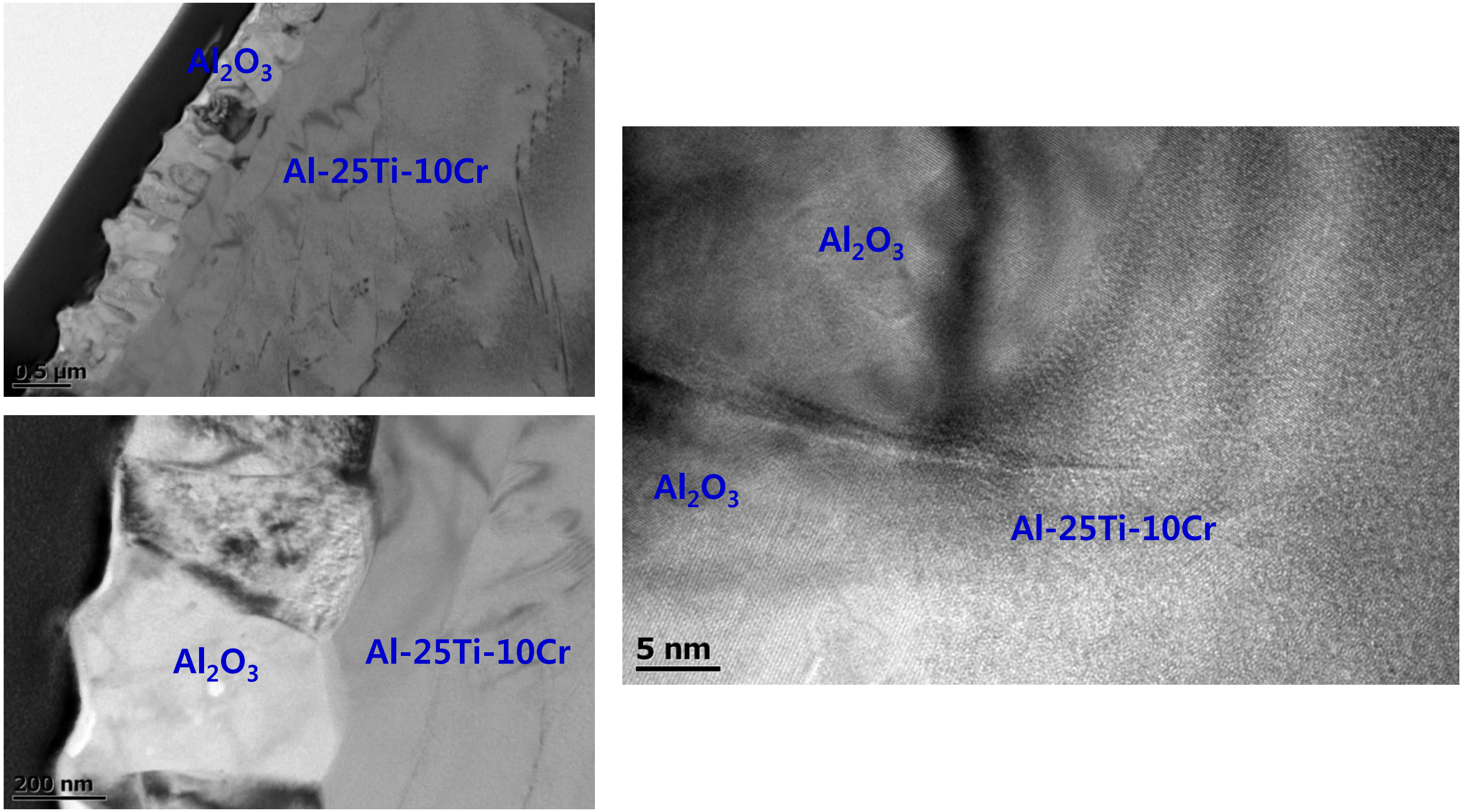


High temperature oxidation behavior



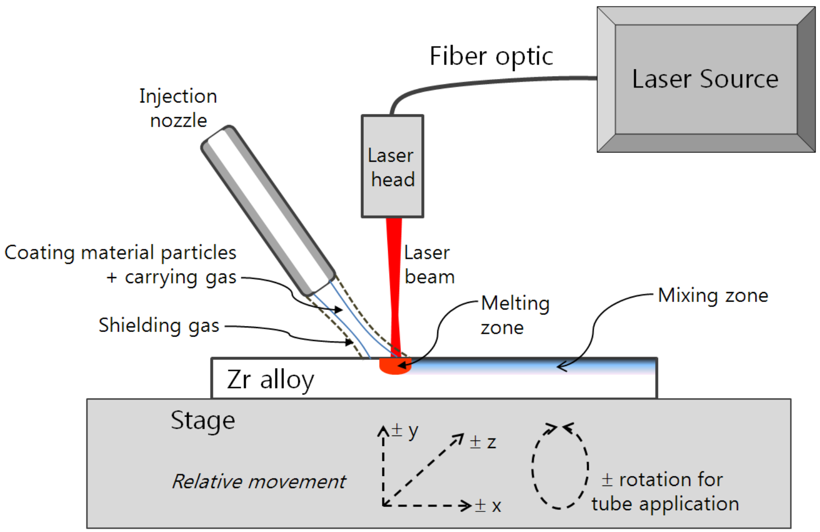
Oxidation behavior of Al-25Ti-10Cr and Al-21Ti-23Cr alloys in 1200°C steam with Zircaloy-4 for comparison.

Oxide microstructure

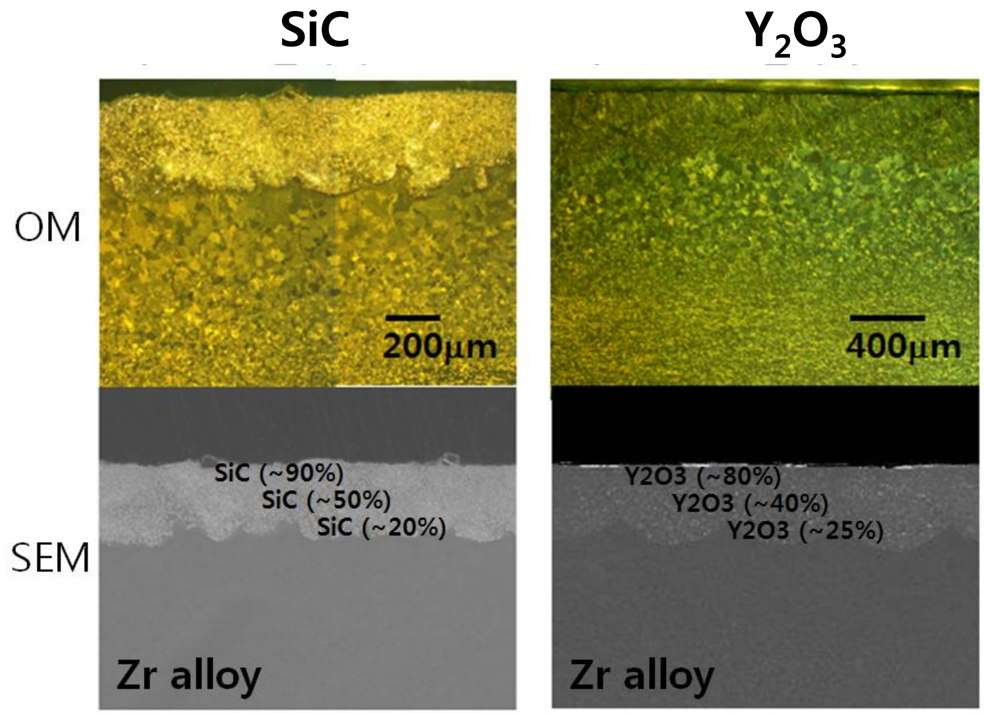


TEM micrographs and high resolution image of the oxide cross-section of Al-25Ti-10Cr alloy after the high temperature oxidation test in 1200°C steam for 2000s.

Laser beam scanning (LBS)

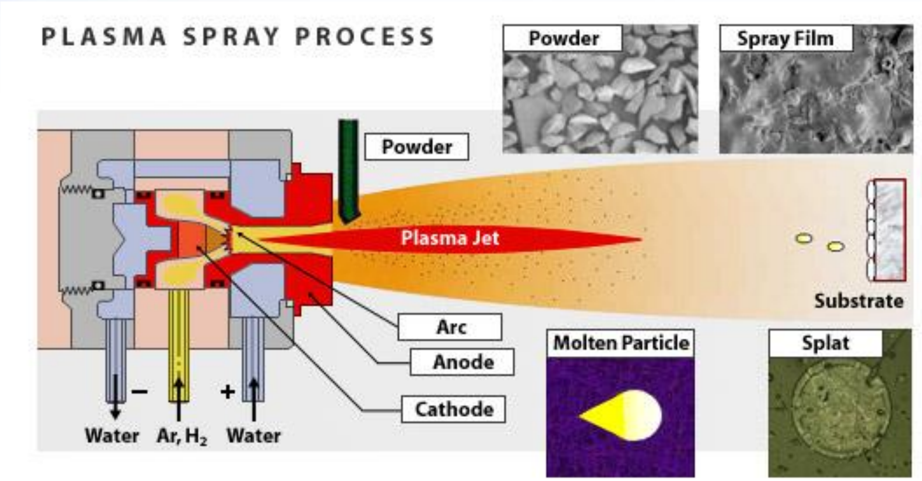


Schematic of the laser beam scanning of the coating materials on Zr alloys plate



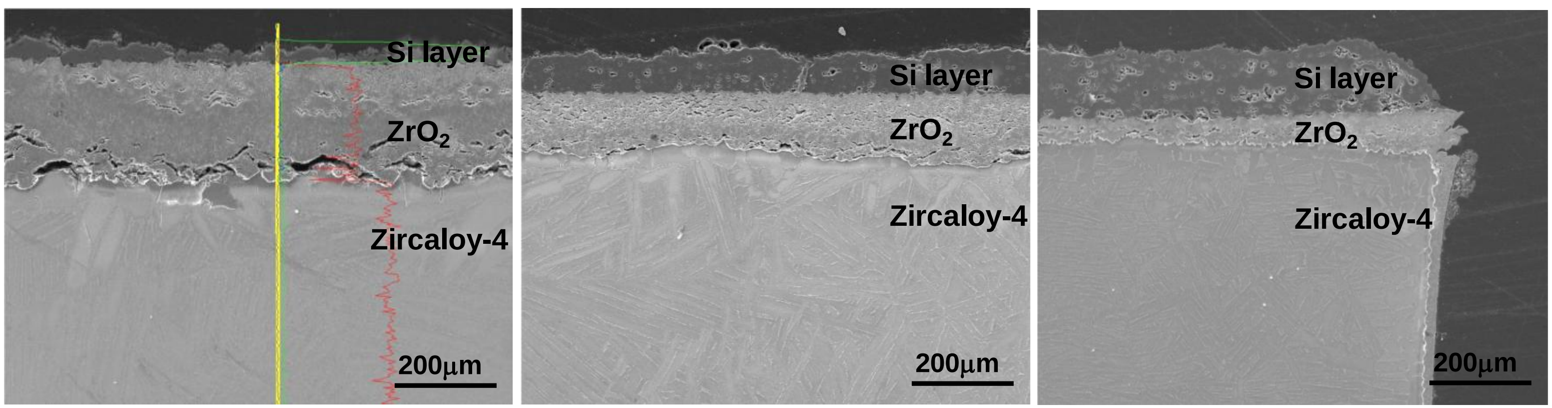
Microstructure of SiC and Y_2O_3 coated on Zr alloys by the laser beam scanning

Plasma spray coating



Surface treatment prior to PS and the post heat treatment were effective to prevent the coated layer from peeling off.

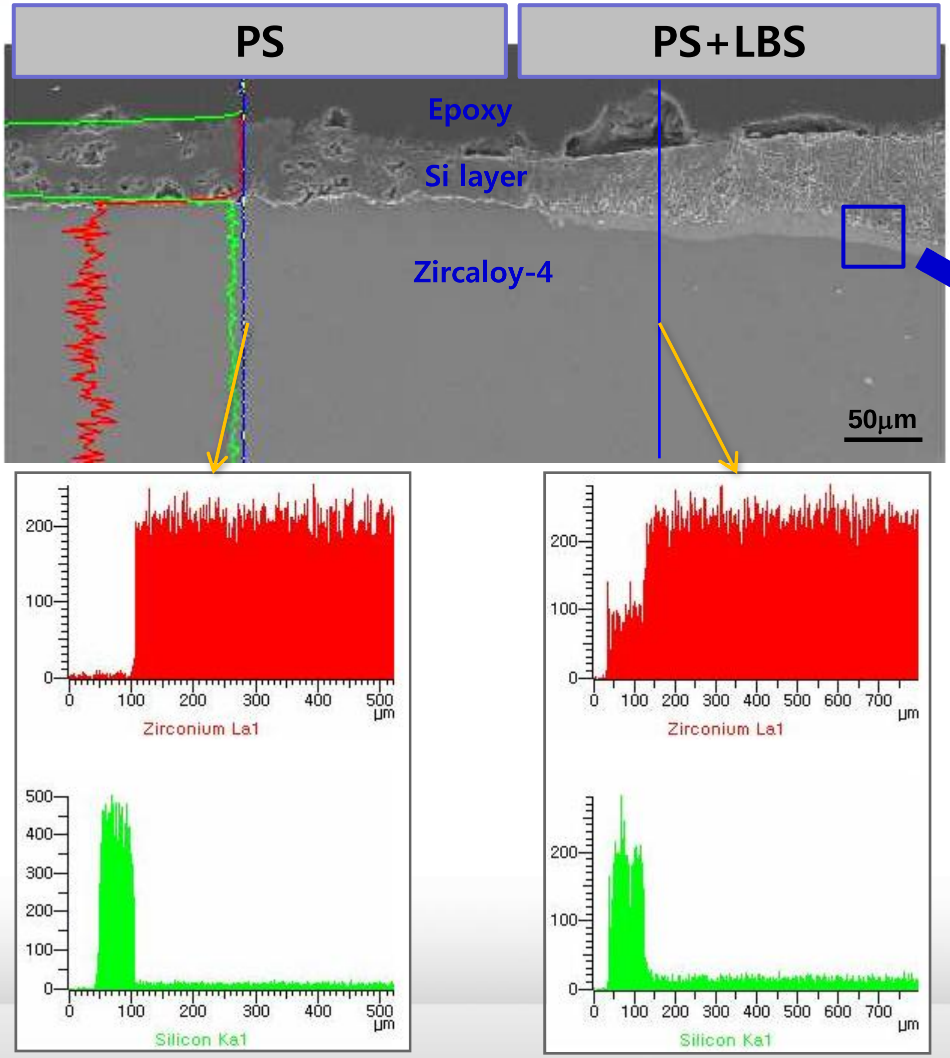
1 spray **3 times of spray** **6 times of spray**

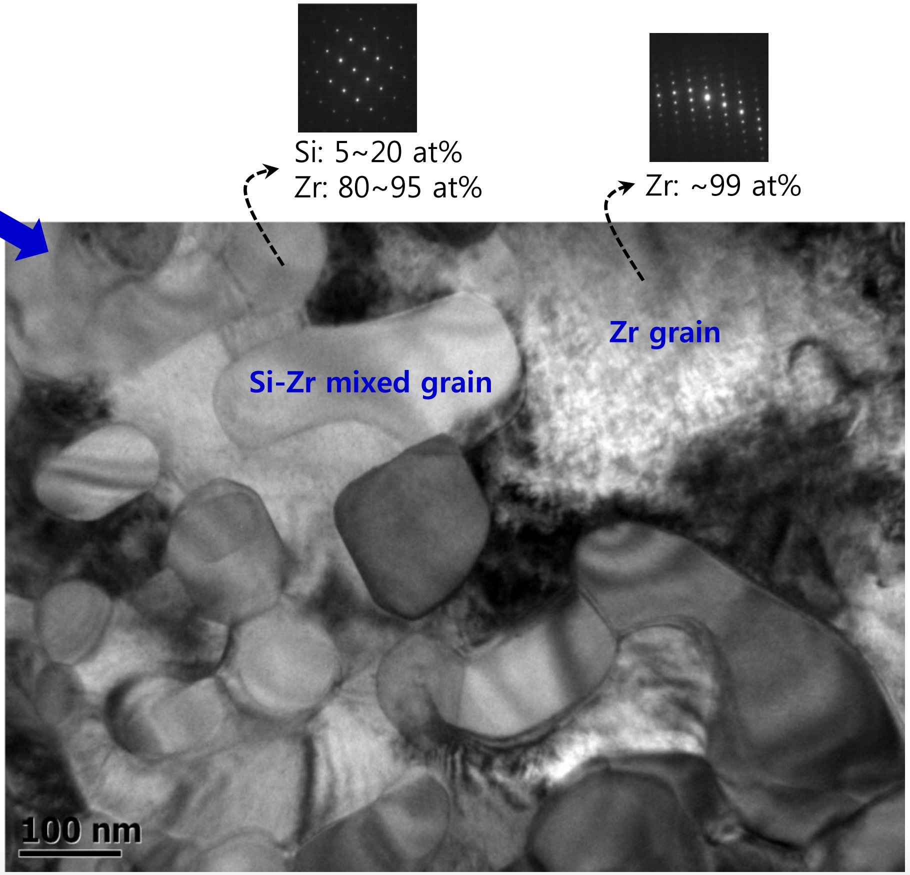


Cross sections of Zicaloy-4 with the plasma sprayed Si coating layer after the high temperature steam oxidation at 1200°C for 2000s.

Plasma spray coating followed by LBS

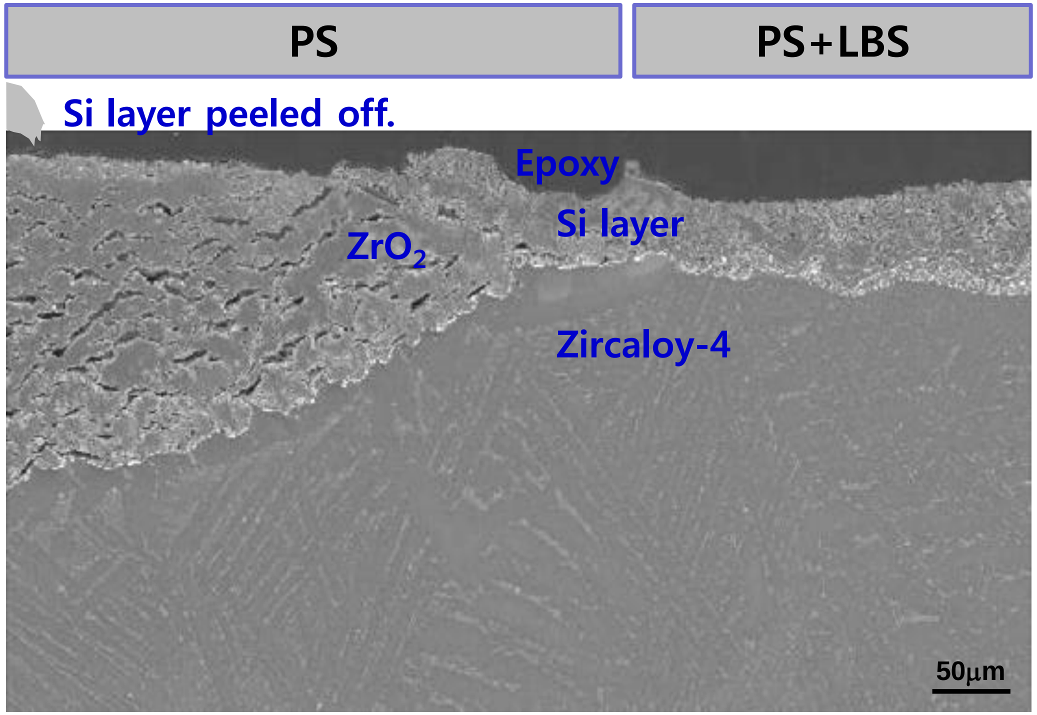
- The plasma sprayed Si layer was scanned by the layer beam to improve the adhesion to Zr alloys and to remove pores.





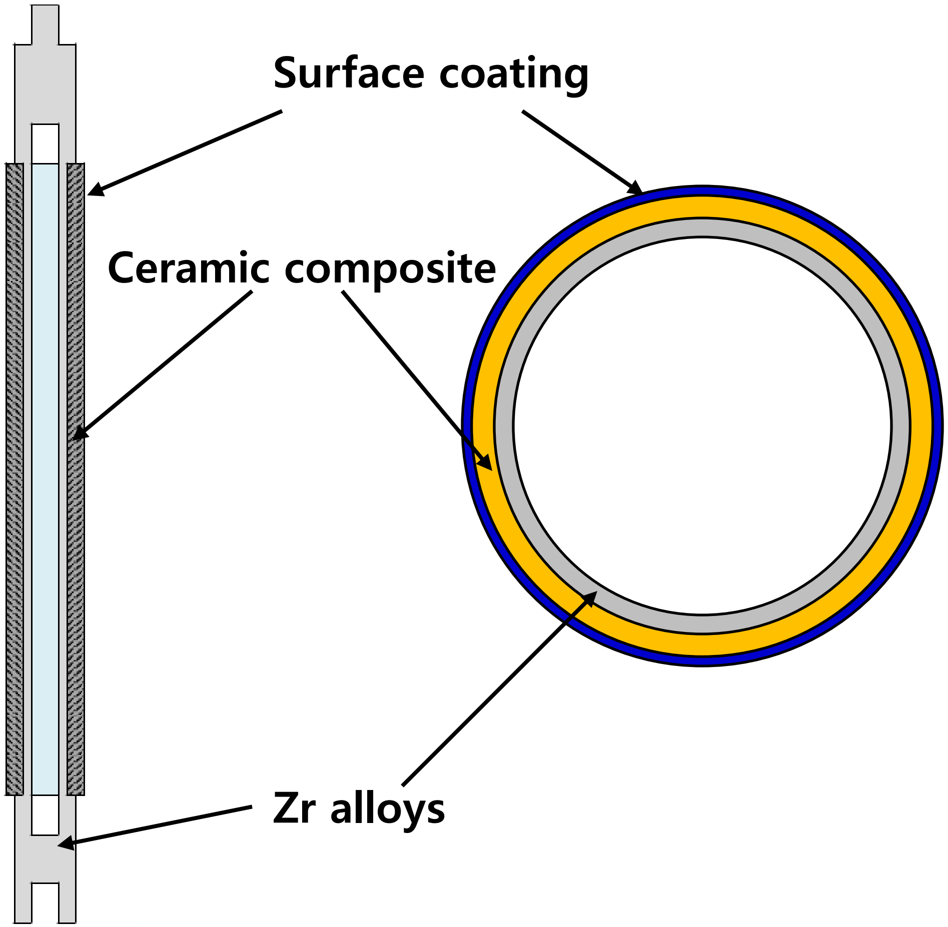
Plasma spray coating followed by LBS

- Si layer formed by PS + LBS is more protective than the layer coated by PS in the high temperature steam oxidation test.



Cross sections of Zicaloy-4 with Si layer by PS and PS + LBS after the high temperature steam oxidation at 1200°C for 2000s.

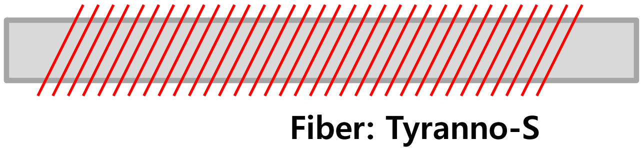
Metal-ceramic hybrid cladding



- Surface coating
  - Corrosion/oxidation barrier: Oxide-based layers
  - Coating process needs to be optimized depending on the coating layer.
- Ceramic composite
  - SiC_f/SiC composite is a primary candidate.
  - Filament winding
  - PIP (polymer impregnation and pyrolysis)
- Zr alloys
  - Manufacturing process needs to be modified to adapt the design change.

Filament winding process development

- Filament winding process are now being developed in collaboration with the specialized industry.



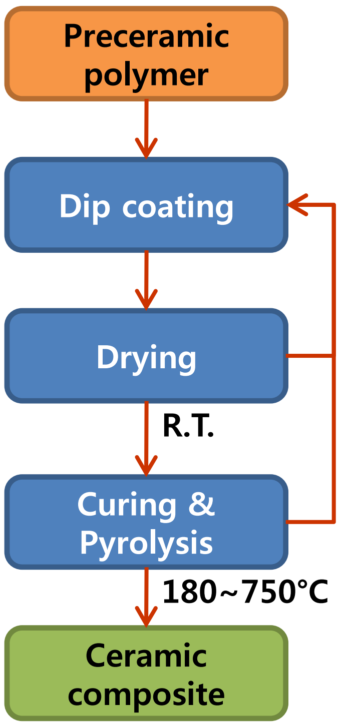
- Dry and wet process for the filament winding will be investigated for CVI and PIP, respectively.

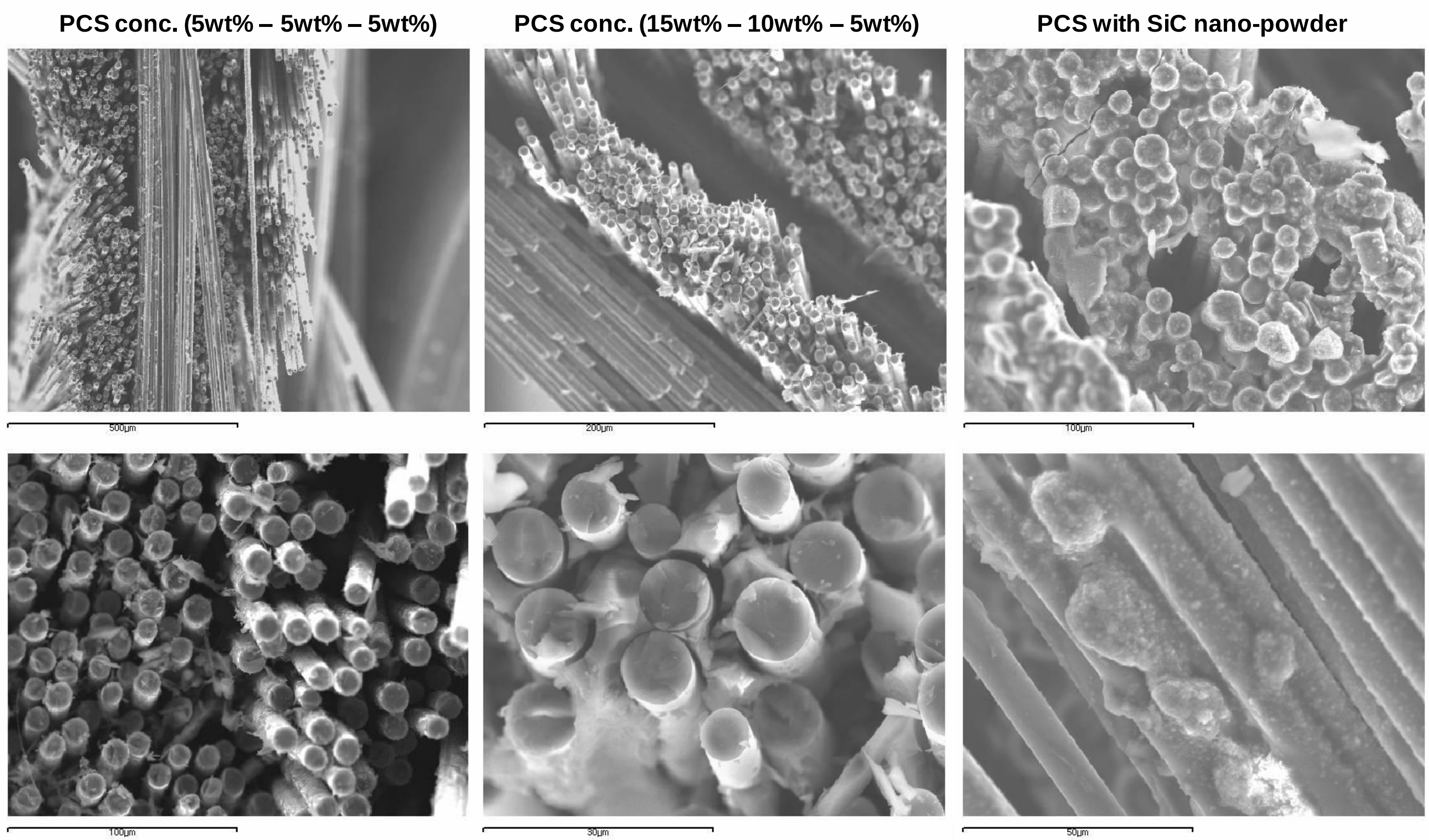
Dry process → CVI

Wet process (with PCS) → PIP

PIP process development

- Effect of the process variables was investigated to develop the optimum PIP process for SiC_f/SiC composite.

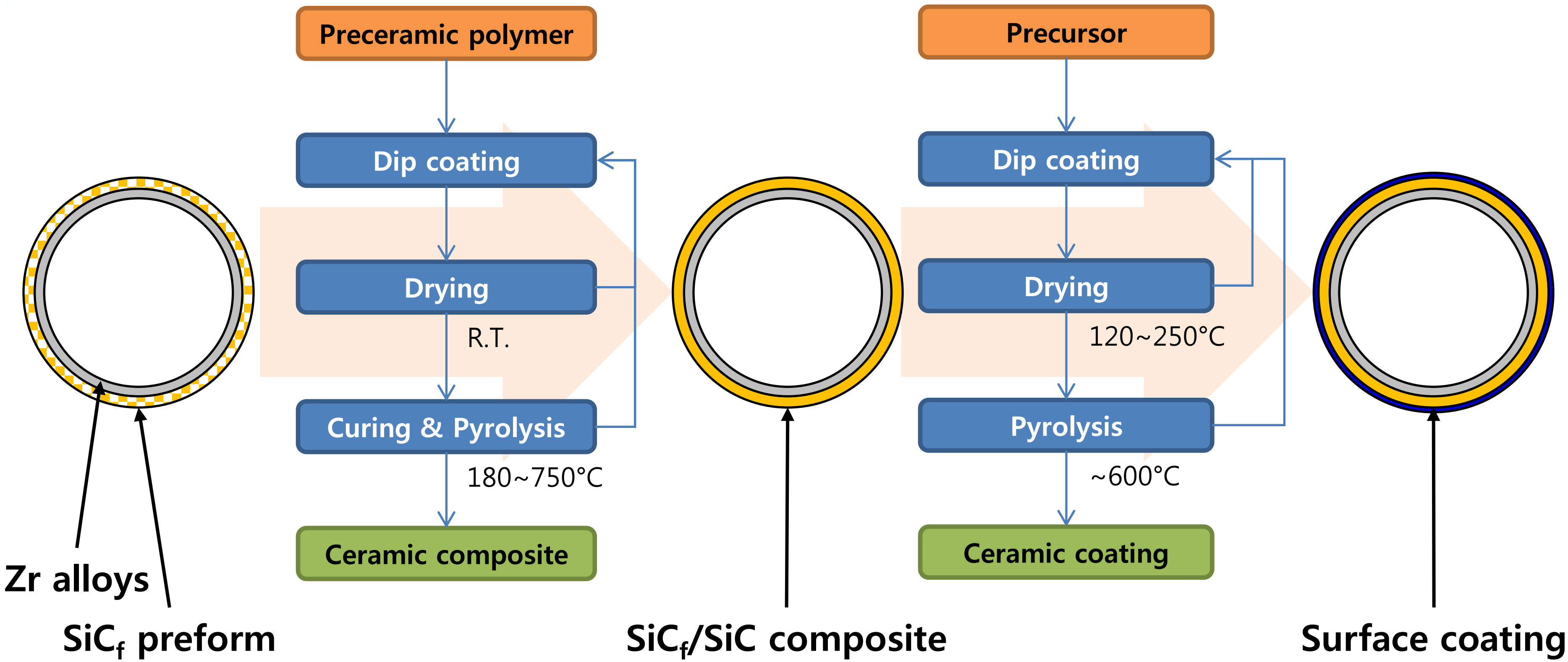




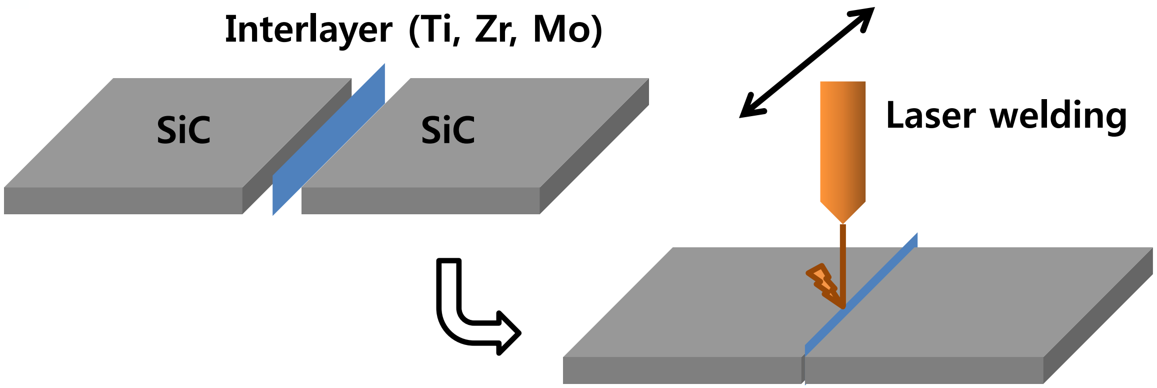
Impregnated SiC_f/SiC composite by PIP

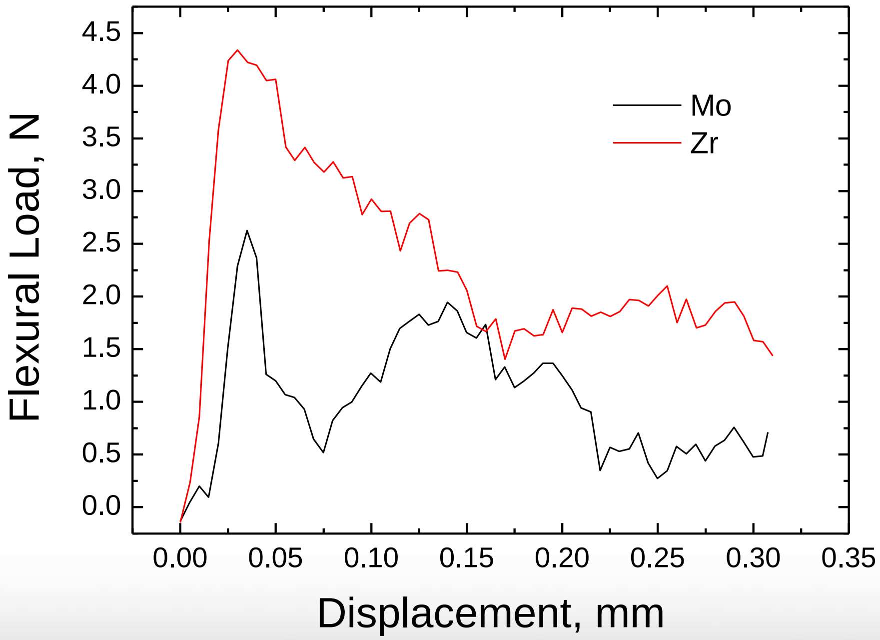
Surface coating of hybrid cladding

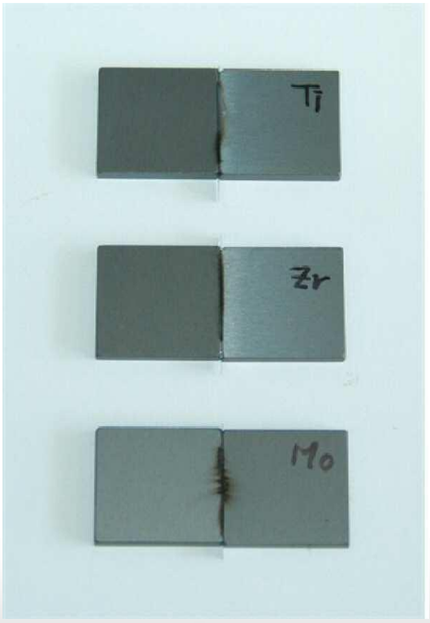
- Sol-gel coating is being investigated as a surface coating of the hybrid cladding to employ the same process with the impregnation.



Laser welding of SiC with interlayer







Summary

- KAERI launched the new project to develop the accident tolerant fuel claddings with the primary objective to suppress the hydrogen emission in the severe accident condition.
- New materials for the oxidation-resistant surface layer on the Zr cladding are being developed together with the compatible surface modification technology.
- PIP for SiC_f/SiC composite and the surface coating technology are being studied to develop the metal-ceramic hybrid cladding.
- Laser welding of SiC with interlayer is being developed for the potential use in the end cap welding of the triplex SiC cladding.